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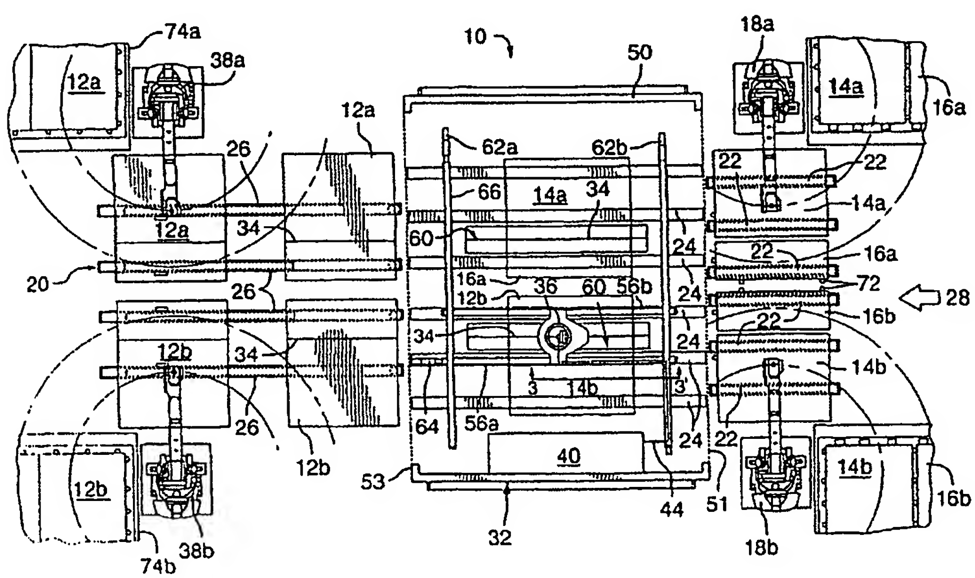

(57) Abstract

A method of laser welding apparatus for use in industrial processing, which is operable to emit laser energy to weld blanks and the like together along a seamline. The emitted laser energy comprises either a single or a multiple beam of two or more coherent light sources. The apparatus is adapted to selectively reposition the orientation on the multiple beam relative to the seamline to achieve maximum weld efficiency having regard to any gaps between the abutting portions of the workpieces to be joined or the relative thicknesses of the sheet blanks to be joined.

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METHOD OF LASER WELDING TAILORED BLANKS

SCOPE OF THE INVENTION

The scope of the invention relates to an improved method for laser welding together two or more sheet blanks along a seam line, and more preferably, to an improved method of using either a single or multiple beams from a yttrium aluminum garnet (YAG) laser to butt weld together tailored blanks.

BACKGROUND OF THE INVENTION

In current day manufacturing processes, it is known to form finished workpiece components by welding together two or more sheet metal blanks of different thicknesses and/or shapes to produce a tailored blank. Tailored blanks are made by joining various sheet material which may have different gauges, surface coatings and/or properties to achieve a finished workpiece having maximum strength with minimum material costs and weight. The automobile industry is an emerging area where tailored blanks are achieving more and more prominence and where such blanks are formed into various automotive parts and vehicle panels. For example, it is known to manufacture automotive doors which incorporate a number of small strategically placed strengthening components by spot welding.

The conventional manufacture of tailored blanks has suffered the disadvantage in that the use of lasers has necessitated that the edges of the component blanks to be joined be prefinished to high tolerances with edges polished to a mirror smooth finish.

SUMMARY OF THE INVENTION

In International application No. PCT/CA98/00153 filed on February 24, 1998, the applicant has disclosed an improved apparatus which may be used to butt weld together sheet metal blanks, and which incorporates a multiple beam laser welding apparatus. In this regard, International application No. PCT/CA98/00153 relates to a welding apparatus used in industrial processing as, for example, would include the

manufacture of tailored blanks used to form automobile components. The apparatus used a multiple beam of two or more coherent light sources to weld together the proximal edge portions of sheet blanks. In addition, a mechanism is provided to selectively position the orientation of the coherent light sources relative to the seam line so that welding may be achieved where a gap between the sheet blanks exists.

It is an object of the present invention to provide a method of optimizing the selective positioning or orientation of the multiple beams relative to the seam line, to ensure a complete welding of the blanks having regard to the gap spacing between the blanks, the relative thicknesses of the abutting portions of the blanks and/or the materials which are to be joined together.

The present invention envisions the use of a YAG laser and more particularly an Nd:YAG laser used to weld the tailored blanks as a most preferred coherent light source. It is to be appreciated, however, that other lasers including CO_2 lasers are also envisioned as being potentially useful with the present method. A comparison of the relevant criteria between Nd:YAG lasers and CO_2 lasers is as shown in Table 1.

Table 1 - Characteristics of Nd:YAG-laser and CO_2-laser

	CO_2-LASER	ND:YAG-LASER
Wave length (μm)	10.6	1.06
Beam quality (mm mrad)	4-15	20-60
Beam delivery	metallic mirrors	glass fiber

Beam focusing	metallic mirrors	glass lens
Intensity profile	Gaussian	flat top
Efficiency	about 10%	2-5%
Polarization	plane or circular	no
Operation	cw or pulsed	cw or pulsed
Operation consume	Gas: He, CO_2, N_2	Kr-lamp
Power (W)	5000-6000*	3000-4000

* in the manufacture of tailored blanks installed lasers

The Nd:YAG laser is capable of producing butt welds on various steel sheets with satisfactory properties at welding speeds meeting the automotive industry demands. In comparison with the CO_2-laser welding the Nd:YAG appears to be preferable as it is more tolerable to joint gap variations, seam edge straightness and offset of the sheared sheets.

Although the present method may be used with single laser beam techniques, the use of a dual-beam or multiple beam technique for laser material processing has the advantage of using increased laser power for faster welding speeds and the possibility of achieving better quality, improved efficiency and flexibility with the system. The two principal purposes by which a dual-beam or other multiple three or more beam technique is introduced to weld different tailored blanks are to increase the processing speed and to extend the processing quality, by welding joints with greater edge and gap tolerances.

Accordingly, in one aspect the present invention resides in a method of using a composite laser beam to weld together adjacent edge portions of two work piece blanks along a seam line, said composite beam including a first laser beam and a second laser beam, each of said first and second laser beams being focused towards a portion of said blanks to be welded at respective focal areas having an optic centre, the optic centers of said first and second laser beams being spaced from each other and defining one end of a focal line of said composite beam, and wherein the effective diameter d_{eff} of the composite beam is defined by the maximum spread of the first and second laser beams in a direction transverse to said weld direction and said seam line, said blanks joined by the steps of:

(a) determining the gap spacing between the abutting edge portions of the blanks to be welded;

(b) adjusting the effective diameter of the composite laser beam to infill the gap substantially in accordance with the formulas:

$$(r_f + d_{off}) = \frac{2g}{(h_2/h_1 - 1)} \quad \text{and where } d_{eff} = 2 \cdot r_f$$

wherein g is the gap spacing, d_{off} is the transverse distance the laser beam center is offset from the seam line, h_1 is the thickness of a first thinner blank and h_2 is the thickness of the second other thicker blank;

(c) altering the rotational angle ϕ of the focal line of the composite beam relative to the seam line substantially in accordance with the formula

$$r_f = \frac{d_f + h \cdot \sin\phi}{2}$$

wherein d_f is the focus diameter of said first laser beam and h is the distance separating the optic centers; and

moving the laser beam along the adjacent portions of said blanks to weld the workpiece blanks together.

In another aspect, the present invention resides in a method of using an apparatus

to butt join an edge portion of a first workpiece blank to an edge portion of a second workpiece blank along a seam line, said first workpiece having a thickness h_1 selected less than the thickness h_2 of the second workpiece blank, the apparatus including,

a laser for emitting a coherent light source to weld said blanks along said seam line and substantially infill any gap between the edge portions, and a controller for controlling said coherent light source, wherein during welding said controller maintains said coherent light source under effective power substantially in accordance with the equation:

$$P_F = S \cdot v \cdot \rho \cdot (c_{sol} \cdot T_m + h_m + c_{liq} \cdot \Delta T)$$

wherein P_F represents the effective laser power, v the welding speed, ρ is the density blank material, c_{sol} and c_{liq} are the specific heat of solid and liquid blank material, T_m the melting temperature, h_m the melting enthalpy of the blank, and ΔT the medium overheating temperature of the melt above the melting point, and wherein S equals the area of weld cross section, and S is determined substantially in accordance with the formula:

$$S = h_2 \cdot (r_f + d_{off}) + h_1 \cdot (r_f - d_{off} - g)$$

wherein r_f is the radius of the coherent light source spot at the seam line in a direction transverse to the seam line, d_{off} is the transverse offset of the center of coherent light source spot from the seam line and g is the gap width between the edge portions.

In a further aspect, the present invention resides in a method of using an apparatus to butt join an edge portion of first workpiece blank to an edge portion of a second workpiece blank along a seam line, the first workpiece blank having a thickness h_1, and the second workpiece blank having a thickness h_2 selected greater than or equal to h_1, the apparatus including,

a laser for emitting a coherent light source as a laser to butt weld said blanks together along said seam line,

said blanks being joined by,

(a) positioning said edge portion of said first blank proximate said edge portion of said second blank,

(b) activating said laser to weld said edge portions while maintaining a gap spacing (g) between said proximate edge portions in accordance with the formula:

$$g=\frac{1}{2}\left(\frac{h_2}{h_1}-1\right)\left(r_f+d_{off}\right)$$

wherein r_f is the radius of the coherent light source in a direction transverse to the seam line, and d_{off} is the distance the center of the coherent light source is transversely offset from the seamline.

BRIEF DESCRIPTION OF THE DRAWINGS

Further objects and advantages of the invention will appear from the following description, taken together with the accompanying drawings in which:

Figure 1 shows the schematic top view of a production assembly line for forming composite work pieces in accordance with the present invention;

Figure 2 shows the schematic side view of a laser welding head used in the production assembly line of Figure 1;

Figure 3 shows the laser welding apparatus shown in the production assembly of Figure 1, taken along lines 3-3' showing the use of a laser to weld sheet blanks;

Figure 4 shows schematically a test production facility for performing dual beam laser welding using Nd:YAG lasers;

Figure 5a shows graphically the change in focus by radii relative to lens distance;

Figure 5b shows graphically the focus spot radii relative to the change in laser power;

Figure 6 shows schematically the processing and welding parameters used in the test installation shown in Figure 4;

Figure 7 shows graphically an energy intensity profile of a test of a dual composite beam used in the method of the present invention;

Figures 8a and 8b illustrate graphically the influence of offset and gap in laser welding;

Figure 9 shows schematically the weld cavity used in the evaluation of weld acceptance;

Figure 10 illustrates schematically the theoretical principal of gap filling by laser welding;

Figure 11 shows graphically the maximum allowable gap in joints as a relation to sheet blank thickness;

Figure 12 shows cross-sectional views of sample welds illustrating the influence of gap on weld concavity;

Figure 13 illustrates graphically the effect of gap and laser beam size as related to weld concavity;

Figure 14 shows schematically the energy distribution of laser welding processes;

Figure 15 illustrates laser energy absorption versus incident angle on a workpiece;

Figure 16 illustrates graphically the calculated coupling rate percentage by workpiece thickness and spot diameter ratio;

Figure 17 illustrates graphically the relationship between welding speed and workpiece thickness;

Figure 18 shows schematically a model used to calculate surface absorption of laser power;

Figure 19 shows graphically the effect of gap and offset on surface absorption;

Figure 20 shows graphically the effect of welding speeds in relation to gap and offset;

Figure 21 shows graphically the welding speed differences between single beam and dual beam welding techniques;

Figure 22 shows cross-sectional views of welds illustrating the effect of head angle on laser weld concavity;

Figure 23 shows graphically the relationship between changing offset and weld concavity;

Figure 24 shows graphically the relationship between gap and concavity;

Figure 25 illustrates the maximum allowable gap in relation to the head angle;

Figure 26 shows the relationship between welding speed and head angle in relationship to 2 to 1.5 mm galv. to x 300 W offset 0.3 mm;

Figure 27 shows schematically a model illustrating surface absorption and head angle;

Figure 28 shows graphically the calculated surface absorption versus head angle;

Figure 29 shows graphically the influence of gap width on welding speed;

Figures 30a to 30c are photographs of weld cross-sections showing the effect of offset on weld concavity;

Figure 31 shows graphically the effect of offset on weld concavity;

Figure 32 shows graphically the effect of a gap on weld concavity using a dual beam technique with an offset of 0.3 mm and a head angle of 6° to weld 2 to 1.5 mm galvanized sheets;

Figures 33a through 33d show photographs of failure locations of weld specimens produced by an Olsen test;

Figure 34 shows the influence of offset and gap on the cracking behaviour of welds;

Figure 35 illustrates schematically the use of dual laser beams to increase the effective beam size;

Figure 36 shows graphically the effect of defocusing the laser beam on welding speed;

Figure 37 shows graphically the effect of rotating a dual beam coherent light source on welding speed;

Figures 38a and 38b illustrate the effect of melting efficiency and welding speed relation to beam diameter;

Figure 39 shows sectional views of sample weld profiles in relation to the rotation angle of the laser beam focal line;

Figure 40 (shown together with Figure 38) illustrates graphically the influence of beam rotation on concavity welding 2.0-1.5 mm sheets;

Figure 41 (shown together with Figure 38) illustrates graphically the relationship of weld concavity and beam rotation angle with a 0.3 mm offset;

Figure 42 illustrates graphically the comparison of positive and negative beam rotation angle versus concavity in welding 2.0-1.5 mm galvanized sheets using a dual beam coherent light source with 0.3 mm offset and a head angle of minus 6°;

Figure 43 illustrates the effect of beam rotation angle on maximum allowable gap;

Figure 44 shows graphically the effect of beam rotation angle, welding speed and gap in automatic welding processes using a dual beam technique;

Figure 45 shows graphically the offset window which exists having regard to gap size in using a dual laser beam welding technique;

Figure 46 shows graphically the effect of head angle on the offset window in which a qualified weld may be achieved;

Figure 47 shows graphically the relationship between the offset window and the thickness ratio of the sheet blanks to be joined;

Figure 48 shows graphically the effect of fluctuating cap size on the offset window;

Figure 49 shows graphically the effect of the rotation angle of a dual beam coherent light source on the offset window;

Figure 50 shows the effect of rotation angle of a dual beam coherent light source on the offset window joining 2.0 to 0.75 mm sheets;

Figure 51 illustrates schematically a prototype tailored blank produced in accordance with a method of the present invention;

Figures 52a and 52b show cross-sectional views of the sample single beam and dual beam weld seams for the prototype shown in Figure 51;

Figure 53 shows a photograph of the Olsen test of the welds conducted on the prototype in accordance with the present invention;

Figure 54 shows a prototype tailored blank used to form a Cadillac rear door and the resulting weld cross-section formed in accordance with the present invention;

Figure 55 shows schematically a prototype tailored blank for a Jeep Cherokee;

Figures 56 to 58 show cross-sectional views of weld joints achieved in forming a prototype Jeep Cherokee tailored blank in accordance with the present invention;

Figure 59 illustrates the results of Olsen testing on weld joints produced in the production of the Jeep Cherokee prototype; and

Figure 60(I) and (II) illustrate various non-linear welds formed in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Reference is made to Figure 1 which shows a production assembly line 10 used in the simultaneous manufacture of two composite tailored blank workpieces 12a,12b. With the assembly line 10 shown, robot vacuum lifts 18a,18b are used to move pairs of sheet metal blanks 14a,16a, 14b,16b from respective supply stacks. Each robot 18a,18b is adapted to move the paired blanks 14a,16a, 14b,16b, respectively onto a conveyor array 20 used to convey the blanks 14a,16a, 14b,16b and finished workpieces 12a,12b along the assembly line 10. The conveyor array 20 consists of three sets of elongated magnet stepping conveyors 22,24,26 which are operable to move the pairs of blanks 14a,16a and 14b,16b and workpieces 12a,12b in the longitudinal direction of arrow 28. The magnetic stepping conveyors which comprise each conveyor set 22,24,26 are shown in Figure 1 arranged in a parallel orientation to both each other and the conveyors in the remaining sets. It is to be appreciated that other conveyor configurations are also possible.

The first set of conveyors 22 are used in the initial positioning of the blanks 14a,16a and 14b,16b in the production line 10, and the conveyance of the positioned blanks 14a,16a and 14b,16b on to the second set of conveyors 24.

Conveyors 24 are provided as part of a laser welding station 32 in which the proximal edge portions of the blanks 14a,16a and 14b,16b are welded together along a seamline by a yttrium aluminum garnet (YAG) laser 36. The conveyors 24 thus are used to move the unwelded blanks 14a,16a and 14b,16b to a welding position, and then

after welding convey the completed workpiece 12a,12b onto the third set of conveyors 26. Conveyors 26 are used to convey the completed composite workpieces 12a,12b to robotic vacuum lifts 38a,38b which lift the workpieces 12a,12b therefrom and onto output stacks.

The production line 10 shown in Figure 1 is configured for the concurrent manufacture of two completed workpieces 12a,12b by a single laser 36. As shown best in Figures 1 to 3, the YAG laser 36 includes a coherent light source generator 40 used to generate two coherent light sources or laser beams, a movable laser head assembly 42 (Figure 2) and a fibre optic coupling 44 (Figures 1 and 3) optically connecting the generator 40 and laser head assembly 42. The fibre optic coupling 44 consists of a bundle of two fibre optic cables (not shown). The energy of the two coherent light sources generated in the generator 40 thus travels via a respective fibre optic cable to the laser head assembly 42.

Figure 2 shows the laser head assembly 42 as including a light emitting laser head 46 from which laser energy is emitted. As disclosed, the laser energy comprises the composite beam which consists of the two coherent light sources. The assembly 42 further includes a support 48 which rotatably mounts the laser head 46, and a drive motor 52 used to rotate the laser head 46 on the support 48. The laser head assembly 42 is provided with a microprocessor controlled seam-tracking sensor 49 (Figure 2) which senses the spacing between the proximal edge portions of each pair of sheet blanks 14a,16a, 14b,16b to be joined. The sensor 49 may, for example, be of the type disclosed in Canadian Patent Application Serial No. 2,199,355 filed March 6, 1997. The sensor 49 includes a separate coherent light source which directs a beam of coherent light downwardly onto the proximal portions of the sheet blanks and a vision or optic sensor for sensing light reflected therefrom. The sensor 49 provides control signals to the drive motors 52 and 64 and the gantry robot 54 to automatically position the laser head 42 so that the composite beam 30 is directed at the weld seam.

Figure 1 shows best the laser 36 as being entirely housed within an enclosure 50. The enclosure 50 is provided with mailbox type entry and exit doors 51,53. Clamping units 60 are also provided within the enclosure 50 for maintaining the sheet blanks in position during welding operations. While numerous types of clamping arrangements are possible, the clamping units 60 preferably each consist of a magnetic clamping unit of the type disclosed in Canadian patent application serial No. 2,167,111, which was laid open to the public on 12 July 1997.

The entire laser head assembly 42 is configured for two axis movement horizontally. The assembly 42 is movable in a first horizontal direction over the conveyors 24 and blanks 14a,16a, 14,16b via a gantry robot 54, along a paired overhead support and slave support 56a,56b. The laser head assembly 42 moves in the first direction via the gantry robot 54, along a track 58 (Figure 3) provided on the overhead support 56a. Each of the pairs of supports 56a,56b are further slidable in a second horizontal direction which is perpendicular to the first on parallel spaced end supports 62a,62b.

The end supports 62a,62b in turn movably support the ends of the parallel supports 56a,56b. A servo drive motor 64 (Figure 1) at the end of support 56a engages a track 66 which extends along one end of support 62a. The movement of the laser head assembly 42 along the supports 56a,56b, and the movement of the supports 56a,56b on the end supports 62a,62b permits the laser head 46 to move over the blanks 14a,16a, 14b,16b in any horizontal direction. The laser head 42 is also vertically movable, and may be inclined relative to a vertical orientation, as for example to the position shown in phantom in Figure 2, by means of a pneumatic slide 68.

During welding operations, two coherent light sources are produced in the coherent light source generator 40. The coherent light sources travel via a respective fibre optic cable in the coupling 44 to the laser head 42 and are emitted therefrom

towards the portion of the seamline 34 to be laser welded. Two laser beams are thus emitted from the laser head 42 to weld proximal edges of the blanks 14a,16a and 14b,16b as a composite laser beam 30 having an elongated focal line which intersects the optical center of each beam.

To achieve optimum welding, experiments were carried out using two 3 kW Nd:YAG lasers and a dual fiber optical cable to explore characteristics of the dual beam welding method and build a series of experimental data, with which to base the development of suitable welding procedures and construct advanced laser welding systems.

a) Test Installation

A research installation, shown in Figure 4, consists of two Haas HL3006D Nd:YAG lasers and a 1.2 m x 1.2 m lab gantry robot and a welding station equipped with a tracking system described with reference to Figures 1 to 3. The laser beams are led into the workstation with a dual step index glass fiber which consisted of two single glass fibers whose ends are jointed together. The beams were focused through a standard Haas 1:1 optic head with two 200 mm lenses. A compressed cross air stream was provided as protective air flow to prevent the optical head from smoke, spray and weld spatter from the welding.

To develop a full understanding of the characteristics of the Nd:YAG laser beam, the optics (focal length) and the glass fiber delivery system used, the focused laser beams were measured. The following documents the results of a complete series of experiments with the laser beam guided by: a) a single fiber and b) a dual fiber, using a PROMETEC™ laser scope. The size, intensity profile and relative position(s) of the focus point for optics with focus lengths of 100, 150, 200 mm lens are accurately determined.

Caustics and Radius Laser Beams

The focused laser beam for the three optics were measured. The minimum focus spot radii were 0.3mm, 0.43mm and 0.56mm respectively, for f = 100, 150 and 200mm optics, as illustrated in Figure 5a. The smaller the optic the steeper the curve rises as it deviates from the true point of focus. The radius reaches a minimum value near the focus point and increases as an exponential condition while the distance is moved away from the focal point. The results of measuring the beam radius at distinct power levels is also shown in Figure 5b, whereby the radius of the focused beam(s) remained almost constant, while the power was changed from 300W to 3000W. That is another advantage of fiber conducted Nd:YAG-laser. A comparison of the beam characteristics for different optics shows the optic with longer focal length *ie:* 200, has a longer rally length. This is to be expected knowing the basics of solid state laser beams, but having the exact data allows for a more accurate setup of the weld parameters. The greater the distance over which the beam radius remains constant the more it increases the stability of the process. Therefore the 200 mm focal lens is selected in the research and the production.

The position of the focus spot for each particular optic is very important because the welds are normally produced while the focus spot is set at the surface of the sheet. The focal position for each of 200 mm optic is 179 mm, measured from the materials surface to the cover of the protective glass. This dimension will remain constant if the lens and the lens's keeper are identical.

The major processing parameters for laser welding of tailored blanks are shown schematically in Figure 6. These parameters can be divided into two groups: (a) the welding parameters; and (b) the properties of the sheets used for the tailored blanks. The first group includes the laser power at the surface of workpiece P_1 of laser 1, P_2 of laser 2, travel speed v, focus position z, angle of the head θ, beam rotating angle φ of the laser beams to the joint and the offset d_{off} from the joint.

Figure 7 reveals, through a three dimensional display, the intensity of the dual beam and the relationship of two spots at 2 x 3000 W. The profile indicates that the

power distribution is almost constant over the full diameter of the beam when it is in focus. Each beam emanates from a 3000 W laser. The diameter of each spot is about 0.6 mm, the same as each single beam. The distance between two focus spot is 1.2mm and there is a space of 0.6mm between two spots. The maximum width of coverage by rotating the dual laser beam to 90° (ie. so that the focal line connecting the optical centers of the beams is transverse to the seam) is 1.8mm. In addition, the power of each spot can be changed individually according to the requirements. It gives a useful method to process some particular joints.

The second group includes materials, coatings, thickness of two sheets, shearing edge condition and gap between the sheets. As will be described, the gap is one of the most important factors affecting the selection of weld parameters, the weld concavity, and the results of the Olsen tests. The set up of welding process is generally described as follows:

1) the laser power is normally selected at the maximal output power of two lasers to achieve the maximal welding speed;
2) the focus position is an important process parameter of laser welding, so that a correct and accurate setup of the focus position is the condition to get a stable and effective welding process. The focus spot of laser beams for welding tailored blanks is preferably located on the surface of the thinner sheet;
3) normally, by welding tailored blanks from 0.8 to 2.0 mm, a head angle of ±6 degrees is proposed. The selection of the head angle is basically dependent on the thickness ratio of a joint. For welding a joint with a large thickness ratio, a positive head angle is proposed, and for joint with small one, a negative angle is preferred;
4) the offset is also an important welding process parameter. It may be determined experimentally to minimize the weld concavity and achieve optimal weld cross-sectioning;
5) the necessity of the beam rotating is based on the maximal gap in joints. It is applied only in case the maximal gap is beyond the gap filling capability of the single beam technique;
6) the welding speed is determined by increasing step by step until the joint is not

completely penetrated. So a maximal welding speed can be found out. The welding speed can be selected at about 90% of the maximal value for a optimally reliable welding process.

Two testing methods were developed to concentrate the investigation on the influence of the offset and gap on welding processing. One was the welding by varying offset (Figure 8a), in which the offset is being changing continuously along the whole joint. At the start of each welding, the offset is zero, at the end of the specimen the offset reaches a designated value, for instance 0.3, 0.6 or 0.9 mm. Occasionally, a certain gap can be added to welding tests. After welding the specimen was checked to find the minimal and maximal offset, at which the sheet is not fully penetrated or a proper weld is not achieved. The specimen was then cut at those positions with special offset values, for example at 0, 0.1mm...etc. to check the weld cross section as well measure the weld concavity. An offset range, in which the weld concavity is below a certain value (typically 10%), can be decided based on Figure 8. In many cases there exists an optimal offset value from these results.

Another was the welding by varying gap, as illustrated in Figure 8b. The two sheets are so clamped that at start of welding there is no gap between the sheets, at the end of the joint a designated gap is set up. Then the width of the gap was measured with thickness gauge and the positions are marked. The welding was carried out at a constant offset (normally near the optimal offset). After welding the specimens were accurately sheared at those marked positions to check weld appearance. A typical result drawn from the testing can also be seen in Figure 8b. Normally the weld concavity increases with larger gapping. The maximal allowable gap can be determined from such a kind of diagrams according to the maximal allowable weld concavity (for example 10% or 15%).

To reduce testing errors caused by the variation of the straightness of sheared edges, short sheets (600 mm long) were used as welding specimens in the research work. Two characteristics of the welded joints have been selected to evaluate the

acceptance of the welds, weld concavity and the Olsen test.

As shown in Figure 9, cross sections of the welded joints are ground (600 grit) and etched (12 % nital) to examine the weld fusion area and measure the minimum through thickness dimension of the weld, under the microscope. The ratio of the measured minimal section to the original thickness of the thinner sheet is the concavity expressed as a percent of the thickness of the thinner sheet. The concavity is an important weld property. To ensure the weld quality and formability, there is a upper limit of 15% for concavity in welding specifications.

The Olsen test is a qualitative formability test. The welded coupon is stressed to fracture. The fracture location is noted. A weld sample is accepted if the crack starts and expands in the base metal and does not have problem in the form process. The Olsen test is much stricter than the form in dies, so that a weld passed Olsen test formability of welds ought not to fail in the die process.

b) Gap Filling by Laser Welding

Using a simple model the relationship among the offset, gap, laser focus spot and thickness of both sheets can be described for a welding processing without additive filler material, as illustrated in Figure 10. Assuming the metal on the edge of the thicker sheet would be melted to fill the gap, the shape of this edge would approximately be triangular. The range of the melted metal would be decided by the laser beam dimension, i.e. the material just under the radiation of the laser beam is melted. To completely fill the gap (S_g) the area S_m of the melted thicker sheet must be equal to that of the gap S_g, thus the following relation exists:

$$S_g = g \cdot h_1 \qquad (3.1)$$

Therefore, the allowable width of gap is:

$$g = \frac{1}{2}\left(\frac{h_2}{h_1} - 1\right)\left(r_f + d_{off}\right) = \frac{1}{2}(TR - 1)(r_f + d_{off}) \qquad (3.2)$$

In the equation, the offset (d_{off}), gap width (g) the focal spot radii (r_f) the thickness h_2 and h_1 of thicker and thinner sheets are shown in Figure 3.1. *TR* is the thickness ratio of welds(h_2/h_1). According to this model the gap will be filled. The following factors must be considered when examining the outcome of the process variables: (a) Increasing the offset (d_{off}); (b) Changing the shape of the molten zone through altering of the head angle will effectively melt more or less of the thicker sheet; and (c) Increasing the focus spot size (r_f) of laser beam through using dual beam or defocusing the beam.

But the offset is limited by laser spot size and gap, i.e. the maximal offset is equal to r_f-g. If the offset is larger than this value, the edge of the thinner sheet cannot be touched and heated by the laser beam. It results in an unstable weld process. Therefore, the maximal gap is:

$$g_{max} = \frac{r_f(TR - 1)}{1 + 0.5(TR - 1)} \qquad (3.3)$$

Figure 11 shows the maximum allowable gap in joints as a function of thickness ratio by two laser beam spot sizes. The r_f = 0.3mm corresponds to a single beam welding, while r_f =0.6mm corresponds to dual beam spots with a rotating angle of 30°. It states, in one side, that the maximum allowed gap has to be considered with the joint configuration. The larger the thickness ratio, the easier to get weld without concavity. On the other hand, by welding a certain joint, to get better gap filling is to use a laser beam with a larger focus spot. In Table 2, the maximum allowable gap by laser welding several typical tailored blanks is listed.

Table 2 The calculated maximal gap by laser welding tailored blanks

Thick	Thin	TR	Max. Gap	Max. Gap

(mm)	(mm)		(single beam d_f 0.6mm)	(dual beam d_f 1.2mm)
1.8	0.8	2.25	0.23 mm	0.46 mm
2.0	1.0	2.0	0.20 mm	0.40 mm
1.3	0.8	1.6	0.14 mm	0.28 mm
1.3	1.0	1.3	0.08 mm	0.16 mm
1.0	0.8	1.25	0.07 mm	0.13 mm

Figure 12 shows the influence of gap on weld cross sections by welding of 2.0 to 0.75 mm galvanized tailored blanks. From this picture, it is evident to observe how the gap is to be filled in the welding process. The laser beam melts the edge of the thick material, which flows down to the joint. In the case of zero or small gap the volume of the melted material on the thick side is larger than the amount which gap needs. Therefore it overflows the thin sheet, a near triangle shaped weld section is formed. If the gap becomes larger, this part of the material will get into the gap, the weld gets flat. Also another useful result is worth notice, namely the largest area of the melted transversal section in the weld is achieved under the zero gap. It means that the smaller the gap, the more amount of material is melted so that the higher effective melting power is needed.

In Figure 13, the influence of laser beam size and thickness ratio on the weld concavity is shown and proves the model introduced above. Generally, for welding tailored blanks with large thickness ratio (TR), there is less problem with the gap filling. The seam even with a gap of 0.3 mm can be still welded, without the concavity of the weld exceeding customers specification, for instance 10%, even using single beam welding technique. Based on the Equation (3.3), the allowable maximal gaps for 2.0 to 1.5 mm sheets is 0.085mm, so that a normal welding technique such as single beam or dual beam in line is insufficient to ensure a weld without concavity, if the gap is too large. For this reason, enhanced dual beam welding techniques such as beam rotation are to be applied for welding low thickness ratio seam with a large gap.

Energy Balance by Laser Welding Tailored Blanks

A stable and continuous welding process is a result of energy (or power) balance among laser power, coupling rate and loss power and effective power, as schematically illustrated in Figure 14. The essential energy for welding comes from the laser beam. The materials absorb a part of laser energy and convert it into heat. This process can be described by using an important number: coupling rate A. It indicates how many percent of the laser energy(power) P_L will be absorbed into the material. The rest (P_R) is reflected on the surface of the materials. The absorbed laser energy can be further divided into two parts. One of them contributes to melt the material to form the seam and is defined as effective power P_F. Another part is power loss into the base metal through heat conductivity and described as P_V. For laser welding process, the absorbed laser power has to cover the total effective power and power loss, so following basic equation is valid:

$$A \cdot P_L = P_F + P_V \qquad (3.4)$$

From the principle of a welding process, this equation states that the absorbed laser power should be equal to the sum of the effective power and power loss. If $A \cdot P_L$ is smaller than $P_F + P_V$, it means not enough power in the joint and can result in no or poor penetration. On the contrary, if $A \cdot P_L$ is larger than $P_F + P_V$, it indicates too much power and can often cause overheating, pinholes, blowing out or even cutting in welds.

The purpose of introducing the energy balance is building a mathematical formula to explore the relationship among the material and welding parameters. It enables the quantification of the maximal speed, the effect of the gap, offset on welding process as well as the requirement on tracking system.

The absorption of laser energy into materials is dependent on their optical properties (temperature dependent), the wavelength and polarization direction of the laser beam and the incidence angle of the laser related to the surface. The relationship

among those parameters is given by Fresnel equation. A typical absorption factor of iron (valid also for normal steel) on Nd:YAG-laser beam (wavelength 1.06 micron) at the melting temperature of iron is illustrated in Figure 3.6.

However by the penetrating welding with "keyhole" mechanism, the coupling rate is not only dependent on the surface absorption, but also a function of the shape of keyhole because the multi-reflection-absorption effect of laser beam. In Figure 16, the coupling rate is shown.

For laser welding tailored blanks, thickness of sheets is in the range of 0.75-3.0 mm, the laser beam diameter is 0.6 mm for 0.6mm glass fiber and a 1:1 focusing optic, so the Thickness/diameter ratio of welding process is in the range about 1.25-5. Then the coupling rate of Nd:YAG-laser welding process verifies between 60-80%. For CO_2-laser welding, it verifies between 35-60%. Therefore the coupling rate using Nd:YAG-laser is expected higher than using CO_2-laser even in penetration welding process with the keyhole mechanism. For laser welding sheets with unequal thickness, the thickness/diameter ratio can be calculated by:

$$Thickness\,/\,diameter\,ratio = \frac{h_2 + h_1}{2d_f} \quad (3.5)$$

The effective power required to heat and fuse weld metal can be calculated according to the following equation:

$$P_F = S \cdot v \cdot \rho \cdot (c_{sol} \cdot T_m + h_m + c_{liq} \cdot \Delta T) \qquad (3.6)$$

In the equation, v is the welding speed, ρ the density of material, c_{sol} and c_{liq} the specific heat of solid and liquid melting blank material, T_m the melting temperature, h_m the melting enthalpy and ΔT the medium overheating temperature of the melt above the melting point. For laser welding a medium overheating temperature of $\Delta T = 0.2\text{-}0.4T_m$ is normally reasonable. S is the area of weld cross section and a function of sheets thickness, offset and gap. It can be calculated as follow:

$$S = h_2 \cdot (r_f + d_{off}) + h_1 \cdot (r_f - d_{off} - g) \qquad (3.7)$$

under the condition $-r_f \leq d_{off} \leq r_f - g$. In the equation, h_2 and h_1 are thicknesses of thick and thin sheets, r_f the radius of laser spot, d_{off} the offset and g the gap width.

The power loss can be approximately expressed as[]:

$$P_v = 4.4 \cdot K \cdot T_m \cdot \frac{h_2 + h_1}{2} \cdot \frac{v \cdot b}{4D} \qquad (3.8)$$

In the equation K is the thermal conductivity, D the temperature conductivity of the material, w the weld width.

d) Theoretical Welding Velocity

From the energy balance as well as equations (3.4), (3.5), (3.6), (3.7) and (3.8), the theoretical welding velocity can be derived:

$$v = \frac{A \cdot P_L}{S_{eff} \cdot \rho \cdot (c_{sol} T_m + H_m + \Delta T \cdot c_{liq}) + 0.55(h_2 + h_1) K w T_m / D} \quad (3.9)$$

For single beam welding, the weld width w is normally larger than the laser spot diameter. According the experimental observation, w can approximately be calculated as $1.3d_f$. So the effective area S_{eff} of weld cross section is determined at between about 1.1 and 1.55, and most preferably is equal to $1.3S$. The medium overheating temperature is ΔT is $0.2T_m$. For dual beam welding, because of higher energy input and two spots in line, the weld width is even slightly larger than single beam welding and a higher overheating of melting pool is expected, so w is taken as $1.4d_f$, ΔT is $0.4T_m$. Using Equation (3.9), the theoretical velocities for welding several typical steel tailored blanks are calculated and compared with the experimental results, as shown in Figure 17. An excellent correspondence between the calculated and experimental values can be observed.

Gaps and offsets influence welding speed in two points. On one side, they have affect on the quantity of melted metal in welds, which is already involved in Equation (3.9). On other side, they change the Absorption factor A. To describe the absorption behavior between laser beam and joint of sheets under different gap and offset, a simple model is here introduced, as shown in Figure 18. The absorption of

laser energy takes place on three places of a joint: a part of laser power is absorbed by the top surfaces of two sheets, whereby the incidence angle of the laser beam is the same as the head angle; the second one is absorbed by the edge of the thick sheet over the thin sheet, whereby the incidence angle of the radiation is $90°-\theta$, the third part of laser power will be absorbed in the gap by a multi-reflection-absorption process which occurs between both edges of thicker and thinner sheets, whereby the incidence angle is equal to $90°-\theta$, too. The proportion of the absorbed laser power is a function of the head angle, diameter of the focused laser beam, width of gap, offset as well thickness of two sheets. In calculating absorption in joints, the incidence angle, gap width, offset as well as thickness of two sheets are also considered. The calculated results for 2.0 - 1.0 mm joint are shown in Figure 19. By the results, it is obvious that the surface absorption is strongly dependent on gap size. For a joint combination, it increases firstly with the gap, then reaches a peak value at a certain gap. If the gap becomes too large, it drops down again. In contrast, the offset has hardly an affect on the surface absorption.

Using Equation (3.9), the model above as well Figure 16, the affect of gap and offset on welding speed can be estimated. For a certain sheet combination, the coupling rate A is calculated by using the result in Figure 15. Then it has to be modified with the results in Figure 19. The calculated welding speeds by different gap and offset are shown in Figure 20.

By inclined laser beam radiation, from zero to a certain gap width, the absorption factor increases with gap, and then it reaches a maximal grad at a certain gap width. This is because the bigger gap, the more percent of laser power can enter into the gap, which will be reflected and absorbed several times between the gap. This results in higher absorption. Also the amount melted metal decreases with gap size. Both factors causes a higher welding speed. If the gap is too big, the absorbed laser energy becomes less because the times of absorption and reflection of laser beam in the gap decrease with the gap size and a part of laser beam passes through the gap without touching the sheets edges. Although the amount of melted metal is reduced, but the loss of laser power through gap

becomes a determined factor. Therefore welding speed decreases. The selection of the speed for a welding process has to be made based on the zero gap and the maximal gap of the sheared sheets to guarantee the proper welding penetration along the whole joint. The offset has almost no affect on coupling rate and only change the amount of melted metal, so that the welding speed decreases with increasing offset.

e) Welding Tailored Blanks with Dual Beam in Line

The welding of tailored blanks with two Nd:YAG-lasers guided by a double glass fiber are detailed hereafter. The double fiber is so aligned that the double focus points of the laser beams and the focal line connecting such points are parallel with the joint (beam in line). The tests concentrate on determining the effect of head alignment, offset the laser beam, gap filling, welding speeds and welding parameters appearance (concavity) as well as properties of the welds using the Olsen formability test.

1. Comparison of Welding Speeds with Dual Beams

One of the purposes using the dual-beam technique in laser welding tailored blanks is that increased laser power results in higher production efficiency, i.e. faster welding speeds can be achieved. To compare the speeds of the dual beam welding technique with the single beam welding, a series of tests on similar thick-thin sheets combinations and under the same test conditions were conducted. The results are shown in Figure 21. The laser power of single beam is 3000W, the dual beam 2x3000W. head angle is ≈ 6 °. The gaps are set from 0 to 0.2mm. The offset varies between 0.15 and 0.3mm according to the thickness of thinner sheet. Studies have indicated that the welding speeds are normally limited by the thickness of both sheets. However, the thinner side plays a more important role by deciding the welding speed. Figure 21 reveals that the welding speeds for different sheets combinations with dual-beam are almost twice as fast as those with single beam. The welding speed is greatly increased with double the laser power. Therefor, the dual beam welding technique can provide possibilities for customers who need higher productivity (welding speed), to

get immediate results, without having to wait for newer Nd:YAG-lasers with higher power. The construction shown in dual beam technique displays an additional advantage of having twin beams in reducing technical risk of welding system. If one laser should be defective and require repair, the other laser can be used at a reduced welding speed, and production would run continuously.

2. Influence of the Head Angle on Welding Process

The head angle is an important processing parameter. In one hand, the head angle determines the direction of the keyhole, the penetration as well as the shape of welding pool. In another hand, the absorption of the laser power into workpiece is strongly dependent on the beam incident angle. To investigate the influence of the head angle on welding process, four head angles were chosen to weld the sheets. Their effects on melting and weld profile are schematically shown in Figure 22.

From Figure 22, it can be seen that there are three head angle ranges which can be selected by welding tailored blanks with different thickness. The first is that the laser beam comes from thinner side to thick side of joints, which is indicated as positive head angle. The second is that the laser beam is set up to be perpendicular to sheet surface, which is zero head angle. The advantage of positive head angle is that the joint is more easily penetrated, because the laser beam has only to penetrate the thinner sheet and to melt some material on the ticker side to fill the gap. A higher welding speed is therefore expected. By using dual beam technique more laser power is available so that the laser beam can be set in the third range, namely the laser beam comes from the thicker side to the thinner side of joints, whereby the head angle is described as negative. The influences of the head angle on weld concavity are shown in Figure 23 (welding by changing offset) and Figure 24 (welding by changing gap). The dependence of the maximal allowable gap on the head angle by a constant offset is illustrated in Figure 25.

Generally, from Figure 23, Figure 24 and Figure 25, it can be seen: weld

concavity decreases with increased offset; there exits an optimal offset to minimize weld concavity; weld concavity increases with gap size, etc. This indicates that the weld concavity can be reduced by setting proper head angle. For welding 2 to 1.5 mm sheets the best gap filling was achieved with a head angle of -6 degree and a joint with 0.18 mm gap. The bigger the negative head angle, the farther the laser beam gets into the thicker sheets and the more material on the thicker side can be melted to flow down into the melting pool. Another advantage of negative head angle in comparison with positive head angle lies in the penetrating direction of the keyhole. By the positive head angle the keyhole is towards the root edge of the thicker sheet, the distance between the keyhole and the bottom of the joint increases with either increasing the offset or the head angle. This distance peferably should not exceed a certain value, otherwise the bottom edge of the thinner sheet will not be fully melted and may result in an improper weld. By the negative head angle the keyhole penetrates joints from the thicker side to the thinner side and is towards the bottom edge of the thinner sheet. The proper increasing of the offset and the head angle at same time does not cause the position changing of the keyhole at the joint bottom. Accordingly, on one side, the more offset and head angle can be set to melt more thicker sheets, on other side, the root of joint can be still melted to get a sound weld. The negative head angle is specially useful for welding the joints with small thickness difference to get better weld filling. Its disadvantage is that melting more material means more laser power and therefor lower welding speed.

From the Figures it is apparent that the worst gap filling is obtained by zero head angle if any gap exits. One reason for this may be caused by the interaction between the keyhole and gap. In this case the keyhole at the sheet bottom may become bigger because a part of keyhole consists of the gap surface. For a deep penetrating welding with keyhole mechanism, it means that more material may be lost through the keyhole. Another reason may lie in the different absorption and interaction between laser beam and joint caused by varying radiating angle.

The relationship between the welding speed and the head angle is shown in

Figure 26. According to the experiments, higher welding speed can be obtained in the range of positive head angle as well at zero head angle. Generally, the welding speed decreases with the decline of the head in negative direction.

The welding speed is decided by the energy balance of the heating process. For laser welding the speed is determined by: 1) absorbed laser power by workpiece, with other word, the absorption; 2) the amount of melted material, under the condition that the heat loss through the conductivity into the base metal would keep same for a certain joint. As discussed above the head angle influences the amount of melting material. The negative head angle can melt more thicker sheets to get better gap filling, but more energy or laser power is needed. The welding speed is naturally lower. By the positive head angle and zero head angle the material to be melted is less in comparison with negative head angle, so that a higher welding speed is expected.

The absorption behavior between laser beam and joint of sheets under different head angles is shown in Figure 27. To simplify calculation process, the percent of the second part is assumed to be equal to the ratio: S_a to focus spot area. In calculating absorption in gap, the incidence angle, gap width, offset as well as thickness of two sheets are also considered. The calculated results are shown in Figure 28. From the calculation, several interesting results can be drawn. The absorption factor by positive head angle is the largest in three head angle ranges. The zero head angle has the smallest absorptance. As well, by zero head angle the absorption of laser power declines with increasing gap. The maximal absorbing of laser power occurs by zero gap. The bigger the gap, the more laser beam goes through the gap without taking interaction with material because of 90° incidence angle to the sheets edges. For welding tailored blanks it means that the welding speed would decrease with increasing gap size, if the amount of melted material should be kept the same.

This conclusion is experimentally confirmed, as shown in Figure 29, in which the welding speed is indicated as a function of the gap size. The welding speed increases

with the gap and reaches its maximum at a gap about 0.1 mm and then decreases. The trend exactly follows the behavior of the absorption of the laser power shown in Figure 28.

Accordingly, the head angle is an important parameter and can strongly influence the welding processing. For a better gap filling the laser welding head should be set in negative angle range. However this kind of head angle setting is only suitable for welding two sheets with less thickness difference (say less than 25%). For welding joint consisting of two sheets with large thickness difference, it should not be recommended because the laser beam has to penetrate thicker side, which means a large loss of welding speed and so far the productivity of the welding processing. For more effective absorption of laser energy and higher welding speed it is meaningful to choose a positive head angle. In this case the proper welding speed is determined by zero gap and the possible maximal gap. The zero head angle has not only the least ability to fill gap, but also the smallest absorption of laser energy, so it should be most possibly avoided in welding tailored blanks.

f) Affect of the Offset on Concavity

By welding typical tailored blanks, the fused weld zone combines part of thinner sheet and a greater part of the thicker sheet. Once there is a gap between the two sheets, it must be filled to form a sound weld. As previously described, to overcome the concavity, good results may be obtained when the beam alignment radiates more into the thicker sheet. The offset of the laser beam is therefor another important processing parameter. Typical effects of the offset on weld cross section are shown in Figure 30. To quantitatively determine the affect of the offset on the welds concavity and to search for a optimal offset for the sheets combination, a series of welding experiments were done using three welding velocities and joints with three sizes of gap. The results of the affect of offset on the concavity of the welds are shown in Figure 31.

Offset plays an important roll when welding tailored blanks as it applies to the size of gap when welding at constant welding speeds. If there is no gap, qualified welds can be achieved with a wide range of offset settings. From an offset of 0-0.3 mm, the weld's concavity is below 10% and the weld is well filled. The weld's concavity decreases with increasing the offset position because of melting more of the thicker sheet material. If a gap exits, a certain offset should be maintained to keep the weld's concavity below 10%. Most preferably, the offset is maintained when the automatic tracking system is employed. If the gap is too large, a qualified weld cannot be achieved. The concavity and undercut often appear in both sides of the weld (Figure 30b).

There exists an optimal offset at which the weld's concavity is a minimum. In tests for a 2.0 mm to 1.5 mm sheet combination the optimal offset is about 0.25-0.3 mm. Above this value any increasing of the offset results in more concavity. However, another phenomenon should be noted, in that there exists an upper limit of offset for different welding speed and gaps. Once the offset exceeds this limit, high quality welds cannot be created. The laser beam(s) heat only the thicker sheet, which is burned out. The thinner sheet is not melted at the bottom corner (Figure 30c). In this case there is a small notch at the root and a sound weld is not available under this condition.

In the range of the optimal offset the welding speed has minimal effect. Welding carried out at higher speeds is, however, preferred because the higher speed leads not only to greater productivity, but also the weld's concavity can be kept below 10% over a much greater offset range, increasing processing tolerance and safety.

g) The Maximum Allowable Gap

The existence of a gap between two sheets to be jointed is considered to be unavoidable, certainly over joint lengths exceeding one meter. Investigations have shown that sheets cut with a normal shear do not have straight edges. As such for any specific welding technique under a certain welding condition, there is a maximum allowable gap up to which a satisfactory weld is achievable.

In Figure 32, the dependence of the weld's concavity on the joint gap is shown. It is not surprising that the weld's concavity increases with increasing gap size. From Figure 32 it is shown that the maximal allowable gap can be read out by setting different maximal weld concavity. For example, the maximum allowable gap is 0.1 mm to 0.15 mm, whereby a concavity measurement of 10 % is obtained, using the dual beam welding technique with 0.3 mm offset, 6° head angle and 2 to 1.5 mm galvanized sheets. It should also be noted that the welding speed can effect the maximum gap. Slowing the welding speed has not proven to be a satisfactory method of filling wider gaps by a constant offset. That is because the slower the welding speed, the greater the loss of metal resulting from evaporating and spraying of the molten material through the keyhole. In order to obtain better joint filling the speed has to be slowed along with a corresponding defocusing of the beam or increasing of the offset at the same time.

The results of Olsen tests carried out to qualitatively investigate the mechanical properties, i.e. the strength and formability of welds are shown in Figure 33. The photographs shown in Figure 33 reveal the failure locations of the welded specimens produced by the Olsen test. The crack initiated in the base metal (normally in the thinner sheet) and extended in the base metal parallel to the joint or cross the welds (Figure 33a and 33b). In these cases the mechanical properties of the welded joints are satisfied. Figure 33c shows the crack initiated in the base metal adjacent to weld in the thinner sheet parallel to the welds. In this situation the joints have satisfactory properties and the condition is not thought to be critical where the crack is initiated and extended in welds (Figure 33d), the joints are not qualified.

Figure 34 show how the offset and gap influence the cracking behavior of the welded joints under the Olsen test. When the offset is too big, the thinner sheet in question is not completely melted and the joint has minimal formability. This condition has to be carefully avoided. Joints with wider gaps and/or welded with improper offset may also fracture at the weld because excessive concavity and undercut reduce the transverse section at the weld considerably. Proper processing parameters will ensure

that joints have no problem with the Olsen test. Cracks initiating and extending in the base materials ensure that the welds have suitable mechanical properties.

h) Application of Dual Beam Technique

Two purposes using dual beam technique into welding tailored blanks are increasing welding speed and extending the processing quality, by welding joints with greater edge/gap tolerance. According to Figure 11, one of the possibilities to get better gap filling is to increase the size of the focus spot. As an example, if the gap is 0.2 mm and offset is 0.3mm, on welding 2 to 1.5 mm sheet, a focus spot with an approximate diameter of 1.8 mm should be necessary for proper gap filling. To meet this technical specification on laser beam, the way for single beam welding is increasing the defocus or using lens with longer focus length. However, a fundamental property of laser beam, *i.e.* the power intensity is strongly reduced in either cases. This may also change the welding mechanism from "keyhole" (deep penetration) welding to normal laser fusion (heat conduction) welding, and so all the advantages of laser welding connected to the high power intensity will be lost.

Laser welding tailored blanks with dual beam technique provides an innovative method to solve this problem. The key processing technique is the rotating dual beam and so increasing the effective beam size to meet the special demands on welding heat sources. From Figure 35, it is easy to understand that the effective beam diameter can be continuously verified by turning the two spots around their common center without reducing the power intensity of the laser beam. The beam rotation provides the maximal flexibility to handle the joints which are very difficult for single beam welding.

The increasing effective beam size, whether by defocusing or rotating laser beam, means melting more material in the workpiece and results in a wider weld. The lower welding speed is therefore expected. In order to determine the influence of the beam size on welding speed using both technical concepts, a compare investigating was carried out welding 2.0 – 1.5 mm galvanized sheets. The results are shown in

Figure 36 and Figure 37. In Figure 36, the beam diameter was determined by Prometec Laser Scope™. In Figure 37, the effective beam diameter was calculated by following equation:

$$d_{eff} = d_f + h \cdot \sin\varphi$$

In the equation, d_f is the focus diameter of a single spot, h is the distance between two focus spots centers, φ is the beam rotating angle. The variation of the welding speed with the laser spot size is clearly shown. From Figures 36 and 37, an important relation between welding speed and spot diameter by welding with defocusing or rotating laser beams exists as seen in Figures 38a and 38b.

For laser welding with single beam, the melting efficiency, which is proportional to the multiplication of welding speed and beam diameter, keeps normally constant for welding a certain joint at a constant laser power up a certain welding speed. It has been proved to be correct experimentally and theoretically with heat transfer equation. This result can also be applied In the case of laser welding with two spots in line (see Figure 38a), in which the multiplication of welding speed and beam diameter stays almost constant or slightly decreases with increasing of the beam diameter. That indicates the welding speed is inversely proportional to beam diameter. In the example above, if a joint with 0.2 mm gap is to be optimally welded, a laser spot of 1.8 mm diameter would be needed and a welding speed should slow down to about 2.7 m/min. However, the same conclusion is not valid for dual laser beam welding by rotating beams. The melting efficiency grows with increasing effective beam diameter. It can be explained with less latent heat losses through conductivity and higher coupling efficiency connected to the aspect ratio depth/focus diameter. Although welding speed slows down still with increasing effective focus diameter (rotating angle), (see Figure 38b), the welding speed by rotating beams is much higher than that of defocusing beams. For welding tailored blank of 2 to 1.5 mm galvanized sheet by 90° beam rotating angle, the welding speed is 5.4 m/min and will be twice as fast as welding by simply defocusing laser at same effective focus diameter.

In Figure 39 photographs of weld cross sections at different beam rotation angles are shown. From these photos the affect of the beam rotation angle can be clearly observed. The width of the weld top surface is decided by the effective beam diameter, namely the beam rotation angle, while the width of the weld bottom is almost independent on the beam rotation angle. The larger the beam size, the wider the top weld.

In addition, the two beams play a different role by welding processing, one of them is mainly used to penetrate the joint to form a sound weld, while another one is mainly used to melt the thicker material to get better gap filling. For positive beam rotation angle, the front or leading beam incidents at the thicker sheet, which heats and melts thicker sheet, while the behind or lagging beam makes the penetration. Because of the greater thickness of the thick side it cannot be fully penetrated. The front laser beam leaves only a bead on plate weld with a half penetration on the thicker side. It can be obviously seen that the weld consists of two melting spurs. The front beam makes an important contribution on welding processing; it melts thicker side of sheet for a better gap filling; it also preheats the joint material, so that the behind beam can penetrate the joint more easily. The welding speed of such a beam arrangement is therefore higher.

The two beams of negative rotation angle are contrary. The front beam penetrates the joint, while the behind beam radiates the thicker side to provide more melting to gap filling. In this case the front beam has to penetrate cold material, so that the welding speed is somehow lower than that of positive beam rotation angle. Because of the preheating effect of the front laser beam the amount of melted material on the thicker side is obviously more. This is particularly the case on smaller beam rotation angle, for example by 30°, a deep melting pool on the thicker side is formed by the behind beam. The two melting pools form together. With this kind of beam rotation the laser power of the behind beam should be properly reduced for a optimal weld profile. This behavior provides another perspective of the dual beam welding technique: welding with laser power combination of two beams. As well, up to a certain beam rotation angle, the profile of weld becomes similar. That can

be seen in Figure 39 from the comparing of weld profiles at 60° as well at -60° beam rotation angle.

The influences of beam rotation angle on weld concavity are shown in Figures 40 and 41 by welding with varying offset and gap. The comparison of weld concavity by welding with changing gap under positive and negative beam rotation angle is shown in Figure 42. The maximal allowable gap by the different beam rotation angle setting is shown in Figure 43.

Accordingly, from the effects of beam rotation angle and welding processing and gap filling, it can be concluded that through the rotation of laser beams, the effective beam size is increased, so that better gap filling can be achieved. As well, by positive beam rotation angle the welding speed is somehow higher. However better gap filling can be obtained by negative beam rotation angle. Generally, with increased beam rotation angle sheets can be optimally welded with a bigger maximal gap. By positive beam rotation angle, the allowed maximal gap increase is not very evident with the beam rotation. In the negative beam rotation range the rotation of laser beam brings much better gap filling. This changing rate is obvious from 0 to 30 degree. Up 30 degree the further rotating of laser beams has no evident affect on the allowed maximum gap.

Table 3 overviews the basic specifications of the dual beam technique for laser welding of 2 to 1.5 mm sheet blanks. Three important characteristics are welding speed, maximum allowed gapping and offset tolerance.

Table 3 Basic technical specifications of dual beam welding process (2 to 1.5mm).

Gap Mm	Power W	Head Angle °	Beam Rotation °	Speed m/min	Offset Mm

0 - 0.10*	3000*	6	-	4.5-5	0.15 - 0.25*
0 - 0.15	2x3000	6	0	9.0	0.15 - 0.30
0 - 0.17	2x3000	-6	0	8.0	0.05 - 0.10
0 - 0.17	2x3000	-6	0	7.0	0.05 - 0.35
0 - 0.18	2x3000	-6	30	7.0	0.25 - 0.35
0 - 0.22	2x3000	-6	-30	6.6	0.05 - 0.50
0 - 0.23	2x3000	-6	-60	6.0	0.05 - 0.75
0 - 0.24	2x3000	-6	90	5.4	0.05 - 0.90

*reference value of single beam welding

The economical and effective welding process is also strongly dependent on the edge state of the sheet blanks. The straightness along the whole length of the sheared edges is an important characteristic because at the worst situation the maximum gap is twice the variation in the straightness of the sheets. That means, if the variation of straightness is 0.05 mm, the maximum gap can be 0.1 mm. The following examples of this procedure are described for welding 2 to 1.5 mm blanks.

Maximum gap of sheets below 0.1 mm

Either single or dual beam welding technique can be chosen only in accordance with demands on productivity. Where the gap is below 0.1 mm, it is not necessary to rotate laser beam. The head angle should be positive and the beam rotation angle should set up at 0 degree to get the highest welding speeds possible. The maximum welding speed is dependent on the beam position without gap, so it is also not necessary to adapt the welding speed to match the gap. The dual beam welding technique is especially attractive on its economical aspect, namely increased costs of about 10-15% but with about 100% higher welding speed. In this case the demand on the accuracy of the tracking system is ± 0.05 mm to keep a optimal offset.

Maximum gap of the sheets about 0.15 mm

The dual beam welding technique should be selected if the gap is about 0.15 mm. If the maximum gap is less than 0.15 mm, the welding process with two beams in line (beam rotation angle 0 degree) should be still optimal, whereby the welding speed is as high as twice the single beam welding. The accuracy of the tracking system should be ±0.075mm. If the maximum gap is in the range of 0.17-0.18mm, the optimal choice remains a welding process with 0 degree beam rotation angle or a small beam rotation angle (say 30 degrees). The laser head further ought to be set in negative angle range. Higher welding speeds need more precise tracking system (8 m/min, ±0.025mm), the lower welding speed, the more tolerant the welding processing (7 m/min, ±0.15mm). The welding speed with two lasers is 40-60% higher than single beam welding. At this negative head angle setting the welding speed does almost not change with the gap, so it is simple to weld at a constant speed determined by the minimal or maximum gap.

Maximum gap exceeds 0.2 mm

If the gap changes between 0 to 0.25 mm along the whole welding joint, it is not possible to get a proper weld without using dual beam welding technique with rotating beams. In this situation there exist two different technical methods which can be considered into the construction of the whole laser welding system. A simple way to do this is the welding at a fixed beam rotation angle, whereby both the beam rotation angle and the welding speed are decided by the maximum gap and zero gap. The disadvantage of this welding process is the slight loss of welding speed. For example, to weld sheets with 0.25 mm gap the welding speed is 5.4 m/min, this is about a 12% improvement in welding speed in comparison with single beam welding techniques.

The preferred method is by welding with automatically adapted beam rotation angle and welding speed. This method is in principle based on the basic relationship between gap, beam rotation angle and welding speed. The sensor integrated in the tracking system detects the gap. The gap width is then sent to the control unit of the

welding system, where an optimal beam rotation angle, as well as the related welding speed will be calculated by using the function among gap, rotation angle and speed. The information will be separated and transferred to the control and drive unit of related servo motors to continuously change the beam rotation angle and the welding speed at same time. The advantage of welding with automatically adapted beam rotation angle and welding speed is optimal utilizing of dual beam technique. For example, if the gap changes smoothly from zero to 0.25mm, an average welding speed of 6.7 m/min can be obtained by from 0 to 90 degree beam rotation angle. This is a 24% higher welding speed compared to welding at a fixed beam rotation angle, and about 40% higher speed than single beam welding technique without yet accounting in the more processing reliability and tolerance that the dual beam welding technique will bring. A simplified alternative technical layout using above principle is welding with two fixed speeds and beam rotation angles. From Figure 44, it is apparent that the welding speed and beam rotation angle do change very slightly, if the gap is smaller than 0.1 mm. Therefore, the beam rotation angle can be set at zero and the welding can be carried out at a higher welding speed. Once the gap is between 0.1 and 0.2 mm, a higher beam rotation angle and a lower welding speed can be set, for example, 30 degrees and 7 m/min as shown in Figure 44 in dash lines. Only two fixed welding speeds and beam rotation angles are needed. The advantages of the layout are the simple construction and control of beam rotating mechanism as well as lower technical demand on sensor for gap width detecting.

As indicated, the offset of the laser beam in relation to the joint is also an very important process parameter. One factor that can result in fluctuation of the offset value is if the edge of the blanks are not a perfectly straight line. Their shape may change by different shearing or cutting processes. Also, the focal distance can vary because of wavy surface of blanks. It can also cause the variation of the offset by declined head angles. Another factor may be if the sheets are somehow not properly qualified on the magnetic bed, or if the position of the seam leaves the central line of the mechanical motion. As well, a slight fluctuation of the pins position may be unavoidable because of wearing or welding spatter on pins after a long time operation.

Lastly, the motion of the axis and the gantry has a limited mechanical precision.

The offset window is defined as a range in which a stable welding process and a qualified weld can be achieved. Generally, there are two critical values to determine a window. The lower limit of the offset is decided by the profile of welds, which means a certain amount of metal has to be melted to fill the joins to reduce the weld concavity. The upper value of the offset is limited by penetration of welds, which means a poor or no penetrated weld has to be avoided. The larger the offset window, the more tolerable the welding process to the fluctuations of materials and the welding systems.

The influence of welding speed on the offset window is shown in Figure 45. By zero gap, it increases with decreasing welding velocity. For the welding practice, that means the upper limit of an offset window can be extended through reducing welding speed to get more penetration. However, if there exists a gap between two sheets, it is reduced by slowing down welding speed. It also can be observed that the offset window moves to a higher range with a gap.

As shown in Figure 46, the head angle can cause the change of the offset windows. Normally, the bigger offset windows can be obtained by setting a positive head angle. On the contrary, the negative head angle results in a smaller offset window. So a positive head angle is generally recommended for a more stable and tolerate welding process. The negative head angle is applied only in case the gap filling becomes a determined factor.

Figure 47 shows the influence of thickness ratio of joints on the offset windows. For joints with larger thickness ratio, it is easy to get good gap filling, as previously discussed. However, the offset window is much smaller than that with smaller thickness ratio. The larger the thickness ratio of joints, the narrower the offset window, and for welding joints with large thickness ratio, a more accurate positioning of laser spot is required.

In welding, the gap typically will change along the whole joint. The possible minimal gap is zero and the maximum gap will be determined by the fit up of two abutting edges to be joined. The offset window can be further reduced because of the fluctuation of gap size, as shown in Figure 48. For instance, by welding 2.0 to 0.15mm tailored blanks with dual beams in line, the offset window is from 0.1 to 0.23 mm for zero gap, and from 0.13 to 0.26 mm for a maximum gap of 0.2 mm. In this case, the lowest offset value is determined by the limitation of the maximum gap which is 0.13 mm, while the highest one by the zero gap, which is 0.23 mm. That means the offset window becomes 0.13-0.23 mm, which is obviously smaller than those of a constant gap. The procedure of determining offset for a welding process is then followed by dividing the offset window into two. The optimal offset should locate just in the center of an offset window. For the example above, the offset should be set at 0.18 mm. It allows a maximal offset fluctuation of ±0.05 mm and coves a gap variation of 0-0.2 mm.

The Nd:YAG-laser welding tailored blanks with dual beam technique shows the capability to welding joints with larger gap. It also provides the capability to expand the offset windows, as illustrated in Figure 49. 2.0-1.5mm blanks were welded at different beam rotation angles. At zero beam rotation angle (beam or focal line in line with the edges to be joined), the offset window is 0.21 mm. If the dual beam is turned to 30°, it becomes 0.5mm, which is more than two times big as that of dual beam in line.

The offset window increases with beam rotation angle. For welding tailored blanks with a large thickness ratio, it normally has a very small offset window and requires a very accurate beam positioning. Through the beam rotating, the offset window can be extended, too. Figure 50 shows an example of welding 2.0 to 0.75 mm tailored blanks. By welding with dual beam in line, the offset window is 0.13-0.26 mm. It will be increased to 0-0.39 mm by using a 30° beam rotation. In welding practice, it means a tolerance of laser spots position of ±0.2 mm comparing with ±0.065mm of

single beam or dual beam in line.

h) Prototype Welding

A prototype GMT 800™ body side ring shown in Figure 51 consisting of four 4 pieces (two pieces 2mm and two 1.0 mm galvanized sheets) was welded along 3 joints with a total weld length of 5.5m(≈18'). It is a typical linear weld. The welding procedure is: first welding A and B; next welding AB and C; and lastly, welding ABC and D. The GMT 800 body sides were produced with both single beam and dual beam techniques. The welding parameters are listed in Table 4.

Table 4 Welding parameters for GMT 800 parts

Welding Technique	Focal Lens	Head Angle	Beam Rotation	Laser Power	Welding Speed	Max. Gap
Single beam	200 mm	6°	-	3000 W	5.0 m/min	0.20 mm
Dual beam	200 mm	6°	0°	2x3000 W	9.0 m/min	0.20 mm
Dual beam	200 mm	6°	15°	2x3000 W	8.0 m/min	0.35 mm
Dual beam	150 mm	9°	30°	2x2800 W	9.0 m/min	0.30 mm

Comparing dual beam welding process with a single one shows the welding velocity increases, so that the welding time of a part is reduced from 66 seconds with single beam to 37 seconds with dual beam in line, and 42 seconds with a beam rotation angle of 30°. The tolerance on gap is increased from 0.2mm to 0.35mm with beam rotation with the result that the welding process is more stable and safe. Table 4 also shows the testing of a lens with 150 mm focal length. The advantage of shorter focal length lies in higher speed under same welding conditions.

Cross sections of various weld seams are shown in Figure 52. It can be seen that very smooth welds can be obtained. On a comparison of single and dual beam welding processes, the weld profile of dual beam welding process look better than single one. A typical Olsen stretch formability test coupon is shown in Figure 53. The

cracking began in the thinner section in the base metal. The parts appear satisfactory and to meet the formability in the die. Except for difficulties in the starting phase, no cracking of the delivered parts in forming process was reported.

A prototype Cadillac™ rear door inner panel is shown in Figure 54 and as will be described hereafter a prototype Jeep Cherokee™ side panel was also formed. The Cadillac weld consisted of two linear welds which are perpendicular to each other. Each part was sheared with the same cutting die, which accounted for very accurate joint fit-up. The gaps measured through all the joints were from 0.1 to 0.35 mm, depending on different shearing.

A typical cross-section of the weld appears in Figure 54. There is no weld concavity shown in the photos. To overcome the small hole which appeared at the intersection of the two welds, the laser power was ramped down over the last ten (10) millimeters of weld 1 to allow the crater to be filled. Subsequently, the laser power was ramped up at the start of weld 2. The blank was welded in one path with the head turning at the corner. The beam was shut down at the end of the long leg and restarted at the corner after the head was rotated.

Welds were produced by using: a) the vision tracking system which maintains exact positioning of the laser beam with respect to the joint, b) in some instances not using any tracking to check the accuracy and stability of the gantry and c) a 1m by 1m gantry and a special procedure which involved a compound angle. Without the tracking system, the sheet qualification was much more critical. Satisfactory welds were obtained when the tracking was not engaged if the prepared edges of the die cut parts were within specification. Parts welded with the tracking system turned on revealed no significant difference in weld appearance and profile. The welding parameters applied in welding the parts are listed in Table 5. Again, welding with dual beam technique allows a much larger gap validation.

Table 5 Welding parameters for Cadillac rear door inner panel

Welding Technique	Focal Lens	Head Angle	Beam Rotation	Laser Power	Welding Speed	Max. Gap
Single beam	200 mm	6°+6° *	-	3000 W	5.0 m/min	0.10 mm
Dual beam	200 mm	6°	0°	2500+3000W	9.0 m/min	0.15 mm
Dual beam	200 mm	6°	30°	2500+3000W	7.2 m/min	0.35 mm

* compound angle

The prototyping parts of the Jeep body sides and the welding sequence are shown in Figure 55. The tailored blank of Figure 55 consists of sheets of three gauges and the first weld is over 2.4 meter long. The whole part is 3.6 meters long. The sheets were very thin, and the minimal thickness ratio of the joint was 1.25 which makes gap filling extremely difficult. In addition, two thickness combinations existed in a single weld which could not be welded using a unique speed. The sheet *A* (0.8 mm thick) and *B* (1 mm) were trimmed to the widths shown on the drawing (Figure 55) and loaded into the gantry machine. They were welded into an intermediate part *AB*. The welded blanks were then sheared to the proper length and angle prior to resetting the part *AB* back into the welding gantry. Part *C* was previously sheared to the proper size and shape. Lastly, the Part *AB* and *C* were jointed together.

For construction of the prototype tailored blank, both single and dual beam welding processes were applied, as listed in Table 6. For welding 1.0 to 0.8 mm sheets, a negative head angle was selected because of the very small thickness ratio. The dual beam welding technique with beam rotation provided a higher welding velocity and the capability to bridge larger gaps in joints. This is especially important for long thin sheets prepared by a normal shearing. Also, a 150 mm focal lens was tested. Its advantage is welding at same speed but requiring lower laser power, which benefits the operating duration of the lamps and reduces the operating cost. For welding second welds, the welding velocity was varied up to the sheets combination. For the section of 1.3-0.8 mm, a slightly higher speed was used.

Table 6 Welding parameters for welding Jeep Cherokee body sides

Welding Technique	Focal Lens	Head Angle	Beam Angle	Laser Power	Welding Speed	Max. Gap
S 1.0-0.8 mm	200 mm	-6°	-	3000 W	7.5 m/min	0.15 mm
S 1.3-0.8 mm	200 mm	+6°	-	3000 W	7.0 m/min	0.20 mm
S 1.3-1.0 mm	200 mm	+6°	-	3000 W	6.5 m/min	0.15 mm
D 1.0-0.8 mm	200 mm	-6°	30°	2800+3000W	12 m/min	0.20 mm
D 1.3-0.8 mm	200 mm	+6°	30°	2600+2800W	10 m/min	0.25 mm
D 1.3-1.0 mm	200 mm	+6°	30°	2600+2800W	9.5 m/min	0.22 mm
D 1.0-0.8 mm	150 mm	-6°	30°	2500+2500W	12 m/min	0.20 mm
D 1.3-0.8 mm	150 mm	+6°	30°	2500+2500W	10 m/min	0.20 mm
D 1.3-1.0 mm	150 mm	+6°	30°	2500+2500W	9.5 m/min	0.20 mm

The typical weld cross-sections are shown in Figures 56 to 58 with Figure 56 showing a 1.0-0.8mm joint and Figures 57 and 58 showing 1.3-1.0mm joints. The welds produced have 0% to 8% concavity maximum by the welding of 1.0 to 0.8 mm sheets, which still meet the profile specifications for sheet steel welds set out in the Auto Steel Partnership standard (proposed '97) for tailor welded blanks. From a comparison of the cross-sections welded by using 150 mm focal lens with those of 200 mm focal lens, there is no obvious difference in the welds.

The Olsen stretch formability dome tests (Figure 59) reveal the fracture taking place in the thinner materials outside the welded joint. The welded joints meet all the specifications for acceptability according to current specifications and no failure at welds was reported.

Non-linear welds are also convinced as the future application in tailored blanks. Vehicle designers are increasingly considering the non-linear welded blanks to optimize the construction and improve the formability of the parts more effectively. In Figure 60, two kinds of non-linear welds are shown. The first part consists of two straight line and three arc welds with separate radii of 100 and 475 mm. The second

one is a complete circle weld with a diameter of 200 mm, which is typically used in constructing shock absorber towers. These two non-linear welds were successfully produced by using the applicant's AWS 3™-axis welding machine shown in Figures 1 to 3 combined with dual beam technique. The dual beam welding technique with a beam rotation angle of 30 degrees decreases the requirement on part positioning and gap tolerance along joints.

During prototyping, the experiences with welding defects and scrap parts were also collected. The purpose of this was to review the scraps produced in the prototyping, and furthermore, to look for the reasons of the scraps to minimize the scrap rate. As an example, the GMT 800 parts produced in the very beginning of the prototyping were chosen. By the welding of more than 600 body side rings, there were 23 left-hand scraps and 12 right-hand scraps to be registered. The detailed information is given in Tables 7 and 8.

Table 7 The left hand parts scraps

Part No.	Weld No.	Defect	Position	Comment
AWS014	BC	Overlap	End	Sheets not properly qualified
AWS025	AB	no weld	Start	Tracking error
AWS026	BC	no penetration	Start	Tracking error
AWS036	AB	no weld	End	Excessive gap
AWS038	AB	welding stopped	End	Sheets not properly qualified
AWS039	CD	welding stopped	End	Sheets not properly qualified
AWS048	BC	overlap	End	sheets not properly qualified
AWS049	CD	welding stopped	End	sheets not properly qualified
AWS052	BC	overlap	End	sheets not properly qualified
AWS058	AB	no penetration	Start	tracking error
AWS069	AB	no penetration	Start	tracking error
AWS082	BC	no penetration	Middle	tracking error
ASW101	BC	welding stopped		laser fault
AWS142	AB	no weld	End	excessive gap

AWS143	CD			wrong sheet
AWS144	BC	cutting		sheet not properly qualified
AWS147	BC	welding stopped		sheets not properly qualified
AWS183	CD	blowing out	End	excessive gap
AWS184	AB	welding stopped	End	sheets not properly qualified
AWS196	AB	cutting	End	excessive gap
AWS259	CD	no penetration	End	tracking error
AWS269	AB	welding stopped	End	sheet not properly qualified
AWS278	AB	no penetration	End	tracking error

Table 8 The right-hand scraps

Part No.	Weld No.	Defect	Position	Comment
AWS414	BC	no welding		one laser not active
AWS428	CD	Cutting	End	excessive gap
AWS430	BC	Cutting	End	excessive gap
AWS450	BC	Cutting		excessive gap
AWS451	BC	Cutting		excessive gap
AWS454	BC	Welding stopped	End	sheets not properly qualified
AWS536	CD	Welding stopped	End	sheets not properly qualified
AWS558	BC	Overlap	Start	sheets not properly qualified
AWS650	BC			wrong welding sequence
AWS653	CD	Welding stopped	End	sheets not properly qualified
AWS688	BC	Welding stopped		sheets not properly qualified
AWS707	BC	Cutting	End	Excessive gap

From Tables 7 and 8, of 35 scraps, half (17 pieces) were caused by improper qualification of the sheets on the magnet bed. One reason was that sheets were not sufficiently pushed against the pins, so that a part of the joint is outside of the tracking window. The welding process is stopped by the tracking system. Another reason is the overlap of thick sheet over thin sheet, all of which occur by qualifying thick sheet against thin sheets (weld number BC). 25% (9 pieces) of the scraps were caused by excessive gaps, resulting in cutting, blowing out and series of pinholes. 7 scraps (20%) occurred as a result of tracking error. The welding defect in this case is no penetration in some local

welds (normally at weld start). In most cases, an evident jumping of the laser beam to the thick side can be observed. As well, 2 scrap pieces resulted from laser fault.

The scrap rate is influenced to a great extend by the qualifying sheets on the gantry. To reduce the scrap rate, proper qualification is important, even though the tracking system is applied. More rigid and stable pins can help improve the quality of the qualification. To prevent overlap of the thicker sheet over thinner one, the thick sheets should preferably be qualified first. The first pin should put as close to the staring point of the welding as possible, thereby reducingd the "lead-in" tracking error. The state of sheared edges play also an important role. In order to reduce the scrap rate, a tight straightness tolerance of the sheets edge is helpful. The tracking parameters should be optimized to reduced the frequency of tracking errors. After these improvements, a very low scrap rate (less than 1%) was achieved during second phase of prototyping.

Figure 1 shows the simultaneous production of two work pieces 12a,12b, each having a linear seamline 34. If desired, however, the present invention may equally be used to weld one, two or more workpieces along straight, curved or angled seamlines.

Although Figures 1 to 3 show a production assembly line 10 which incorporates a single laser 36 used to weld pairs of blanks 14a,16a 14b,16b together, the invention is not so limited. If desired, two or more lasers could be used, each with its own movable laser head for simultaneously welding a respective pair of blanks 14,16 along a seamline.

Although the preferred embodiment of the invention discloses the apparatus as including a sensor 49 for continuously sensing the spacing between the sheet blanks 14, the invention is not so limited. In a more cost effective embodiment, the sensor 46 may be omitted. With such a configuration, the positioning of the laser head 42 may be programmed or continuously manually adjusted by an operator concurrently as welding operations are performed. Alternately, the laser head 42 may be moved to a fixed initial position which is maintained constant during welding, as for example, when blanks 14 of

different thicknesses are to be joined.

While the preferred embodiment of the invention discloses the coherent light source generator 40 as generating two separate laser beams, if desired, the energy source could be used to generate a single coherent light source which is separated into two or more laser beams in or en route to the laser head 42. Similarly while two coherent light sources are disclosed as being used for welding, a single beam or multiple beams of three, four or even more coherent light sources could also be used.

Although the detailed description describes and illustrates preferred embodiments of the invention, the invention is not so limited. Many modifications and variations will now occur to persons skilled in the art. For a definition of the invention reference may be had to the appended claims.

Table of Symbols

A	Absorption or coupling rate
b	weld width
c_{sol}	specific heat of solid material
C	specific heat of liquid material
D	temperature conductivity of the material
d_f	diameter of laser beam
d_{eff}	effective beam diameter
d_{off}	offset of laser beam to joints
f	focal length of lens
g	width of gap
Hm	melting enthalpy of material
h	thickness of sheets
h_1	thickness of the thinner sheet in a joint
h_2	thickness of the thicker sheet in a joint
K	thermal conductivity of material
P_L	laser power (output @ workpiece)
P_F	effective power (absorbed power)
P_V	loss power through heat conductivity
r_f	radius of laser beam
T	temperature
T_m	melting temperature of material
TR	thickness ratio of joint
v	welding speed
α	beam incident angle
φ	beam rotation angle
θ	optical head angle
ρ	density of material
ΔT	the medium overheating temperature

We claim:

1. A method of using a composite laser beam to weld together adjacent edge portions of two work piece blanks along a seam line, said composite beam including a first laser beam and a second laser beam, each of said first and second laser beams being focused towards a portion of said blanks to be welded at respective focal areas having an optic centre, the optic centers of said first and second laser beams being spaced from each other and defining one end of a focal line of said composite beam, and wherein the effective diameter d_{eff} of the composite beam is defined by the maximum spread of the first and second laser beams in a direction transverse to said weld direction and said seam line, said blanks joined by the steps of:

(a) determining the gap spacing between the abutting edge portions of the blanks to be welded;

(b) adjusting the effective diameter of the composite laser beam to infill the gap substantially in accordance with the formulas:

$$(r_f + d_{off}) = \frac{2g}{(h_2/h_1 - 1)} \qquad \text{and where } d_{eff} = 2 \cdot r_f$$

wherein g is the gap spacing, d_{off} is the transverse distance the laser beam center is offset from the seam line, h_1 is the thickness of a first thinner blank and h_2 is the thickness of the second other thicker blank;

(c) altering the rotational angle ϕ of the focal line of the composite beam relative to the seam line substantially in accordance with the formula

$$r_f = \frac{d_f + b \cdot \sin\phi}{2}$$

wherein d_f is the focus diameter of said first laser beam and b is the distance separating the optic centers; and

(d) moving the laser beam along the adjacent portions of said blanks to weld the workpiece blanks together.

2. The method of claim 1 wherein said laser beam is moved along the adjacent portions wherein at a velocity substantially in accordance with the formula:

$$v = \frac{A \cdot P_L}{S_{eff} \cdot \rho \cdot (c_{sol} T_m + H_m + \Delta T \cdot c_{liq}\ ) + 0.55(h_2 + h_1) K w T_m / D}$$

wherein A is the coupling rate of absorbed laser energy power;, P_L is the laser power, S_{eff} is the effective cross-sectional area of the weld, ρ is the density of the material to be welded, c_{sol} and c_{liq} are the specific heat of solid and liquid melting blank material, T_m is the melting temperature of the blank material, H_m is the melting enthalpy of the blank material, ΔT is the medium overheating temperature, K is the thermal conductivity of the blank material, w is the weld width and D is the temperature conductivity of the blank material.

3. The method of claim 1 wherein the gap spacing of said adjacent portions is determined by a gap sensor immediately prior to said step of moving the laser beam therealong, and said step of altering the rotation angle of the focal line is performed continuous as said laser beam is moved.

4. The method of claim 1 wherein the focal area of the first laser beam substantially equals the focal area of the second laser beam.

5. The method of claim 1 wherein each of the workpiece blanks is formed from a common metal selected from the group consisting of steel, steel aloys, aluminum, aluminum alloys and titanium.

6. The method as claimed in claim 1 wherein the laser offset (d_{off}) is predetermined by test welding together substantially straight edges of two test sheet blanks, each having a respective thickness equal to h_1 and h_2, by the steps of,

arranging the straight edges of said test blanks proximate to each other and substantially in parallel,

laser welding said proximate edges while changing the laser path offset relative thereto to form a test weld seam,

analysing the test weld seam profile to determine the optimum offset distance from

the proximal edges achieving the desired weld characteristics, and

setting the laser offset (d_{off}) substantially equal to the determined optimum offset distance.

7. The method as claimed in claim 6 wherein the offset of the laser beam is changed at a constant rate as the proximate edges are welded.

8. The method as claimed in claim 1 wherein a maximum allowable gap is predetermined by test welding together substantially straight edges of two test sheet blanks, each having a respective thickness equal to h_1 and h_2, by the steps of,

arranging the straight edges of said test blanks proximate to each other and with a gap spacing between the proximate edges varying constantly from a minimum spacing to a maximum spacing,

laser welding the proximate edges of the test blanks while maintaining the laser beam offset a constant distance from the proximate edge of one test blank to form a test weld seam,

analysing the test weld seam profile to determine the maximum gap spacing permitting the formation of the desired weld characteristics, and

wherein during said step of moving the laser beam maintaining the gap spacing between the abutting edge portions of the blanks equal to or less than the maximum gap spacing.

9. A method of using an apparatus to butt join an edge portion of a first workpiece blank to an edge portion of a second workpiece blank along a seam line, said first workpiece having a thickness h_1 selected less than the thickness h_2 of the second workpiece blank, the apparatus including,

a laser for emitting a coherent light source to weld said blanks along said seam line and substantially infill any gap between the edge portions, and a controller for controlling said coherent light source, wherein during welding said controller maintains said coherent light source under effective power substantially in accordance with the equation:

wherein P_F represents the effective laser power, v the welding speed, ρ is the

$$P_F = S \cdot v \cdot \rho \cdot (c_{sol} \cdot T_m + h_m + c_{liq} \cdot \Delta T)$$

density blank material, c_{sol} and c_{liq} are the specific heat of solid and liquid blank material, T_m the melting temperature, h_m the melting enthalpy of the blank, and ΔT the medium overheating temperature of the melt above the melting point, and wherein S equals the area of weld cross section, and S is determined substantially in accordance with the formula:

$$S=h_2 \cdot (r_f + d_{off}) + h_1 \cdot (r_f - d_{off} - g)$$

wherein r_f is the radius of the coherent light source spot at the seam line in a direction transverse to the seam line, d_{off} is the transverse offset of the center of coherent light source spot from the seam line and g is the gap width between the edge portions.

10. The method as claimed in claim 9 wherein the medium overheating temperatre ΔT is selected at between 0.2 to 0.4 T_m.

11. The method as claimed in claim 9 wherein the laser offset (d_{off}) is predetermined by test welding together substantially straight edges of two test sheet blanks, each having a respective thickness equal to h_1 and h_2, by the steps of,

arranging the straight edges of said test blanks proximate to each other and substantially in parallel,

laser welding said proximate edges while changing the laser beam path offset relative thereto to form a test weld seam,

analysing the test weld seam profile to determine the offset distance from the test weld seam achieving the desired weld characteristics.

12. The method as claimed in claim 9 wherein a maximum allowable gap is predetermined by test welding together substantially straight edges of two test sheet blanks, each having a respective thickness equal to h_1 and h_2, by the steps of,

arranging the straight edges of said test blanks proximate to each other and with a gap spacing between the proximate edges varying constantly from a minimum spacing to a maximum spacing,

laser welding the proximate edges of the test blanks while maintaining the laser beam offset a constant distance from the proximate edge of one test blank to form a test

weld seam,

analysing the test weld seam profile to determine the maximum gap spacing permitting the formation of the desired weld characteristics, and

wherein during welding of said first and second workpiece blanks maintaining the gap spacing between the edge portions equal to or less than the maximum gap spacing.

13. A method of using an apparatus to butt join an edge portion of first workpiece blank to an edge portion of a second workpiece blank along a seam line, the first workpiece blank having a thickness h_1, and the second workpiece blank having a thickness h_2 selected greater than or equal to h_1, the apparatus including,

a laser for emitting a coherent light source as a laser to butt weld said blanks together along said seam line,

said blanks being joined by,

(c) positioning said edge portion of said first blank proximate said edge portion of said second blank,

(d) activating said laser to weld said edge portions while maintaining a gap spacing (g) between said proximate edge portions in accordance with the formula:

$$g=\frac{1}{2}\left(\frac{h_2}{h_1}-1\right)(r_f+d_{off})$$

wherein r_f is the radius of the coherent light source in a direction transverse to the seam line, and d_{off} is the distance the center of the coherent light source is transversely offset from the seamline.

14. The method as claimed in claim 13 wherein welding is performed by moving said coherent light source along the seamline at velocity v substantially according to the equation:

$$v=\frac{A\cdot P_L}{S_{eff}\cdot\rho\cdot(c_{sol}T_m+H_m+\Delta T\cdot c_{liq})+0.55(h_2+h_1)KwT_m/D}$$

wherein A is the coupling rate of absorbed laser energy power:, P_L is the laser power, S_{eff} is the efffective cross-sectional area of the weld, ρ is the density of the material to

be welded, c_{sol} and c_{liq} are the specific heat of solid and liquid melting blank material, T_m is the melting temperature of the blank material, H_m is the melting enthalpy of the blank material, ΔT is the medium overheating temperature, K is the thermal conductivity of the blank material, w is the weld width and D is the temperature conductivity of the blank material.

15. The method according to claim 14 wherein w is calculated by the formula of $1.4d_f$, and where $d_f = 2r_f$.

16. The method of claim 13 wherein said coherent light source comprises a composite beam including at least a first laser beam and a second laser beam.

17. The method as claimed in claim 13 wherein the laser offset (d_{off}) is predetermined by test welding together substantially straight edges of two test sheet blanks, each having a respective thickness equal to h_1 and h_2, by the steps of,

arranging the straight edges of said test blanks proximate to each other and substantially in parallel,

laser welding said proximate edges while changing the coherent light source path offset relative thereto to form a test weld seam,

analysing the test weld seam profile to determine the optimum offset distance from the test weld seam achieving the desired weld characteristics, and

setting the laser offset (d_{off}) substantially equal to the determined optimum offset distance.

18. The method as claimed in claim 13 wherein a maximum allowable gap is predetermined by test welding together substantially straight edges of two test sheet blanks, each having a respective thickness equal to h_1 and h_2, by the steps of,

arranging the straight edges of said test blanks proximate to each other and with a gap spacing between the proximate edges varying constantly from a minimum spacing to a maximum spacing,

laser welding the proximate edges of the test blanks while maintaining the laser

beam offset a constant distance from the proximate edge of one test to form a test weld seam,

analysing the test weld seam profile to determine the maximum gap spacing permitting the formation of the desired weld characteristics, and

maintaining the gap spacing between the edge portions of the blanks equal to or less than the maximum gap spacing.

19. The method of claim 13 wherein said laser further includes a controller, wherein during welding said controller maintains said coherent light source under effective power substantially in accordance with the equation:

$$P_F = S \cdot v \cdot \rho \cdot (c_{sol} \cdot T_m + h_m + c_{liq} \cdot \Delta T)$$

wherein P_F represents the effective laser power, v the welding speed, ρ is the density blank material, c_{sol} and c_{liq} are the specific heat of solid and liquid melting blank material, T_m the melting temperature, h_m the melting enthalpy of the blank, and ΔT the medium overheating temperature of the melt above the melting point, and wherein S equals the area of weld cross section, and S is determined substantially in accordance with the formula:

$$S = h_2 \cdot (r_f + d_{eff}) + h_1 \cdot (r_f - d_{eff} - g)$$

20. The method of claim 16 wherein each of said first and second laser beams and focused towards a portion of said blanks to be welded at respective focal areas having an optic centre, the optic centers of said first and second laser beams being spaced from each other and defining one end of a focal line of said composite beam, and wherein the effective diameter d_{eff} of the composite beam is defined by the maximum spread of the first and second laser beams in a direction transverse to said weld direction and said seam line, said blanks joined by the steps of:

(a) determining the gap spacing between the abutting edge portions of the blanks to be welded;

(b) adjusting the effective diameter of the composite laser beam to infill the gap substantially in accordance with the formulas:

$$(r_f + d_{eff}) = \frac{2g}{(h_2/h_1 - 1)} \quad \text{and where } d_{eff} = 2 \cdot r_f$$

(c) altering the rotational angle ϕ of the focal line of the composite beam relative to the seam line substantially in accordance with the formula

$$r_f = \frac{d_f + b \cdot \sin\phi}{2}$$

where d_f is the focus diameter of said first laser beam and b is the distance separating the optic centers; and

(d) continually altering the rotation angle of the focal line as the composite beam moves along the adjacent portions of said blanks.

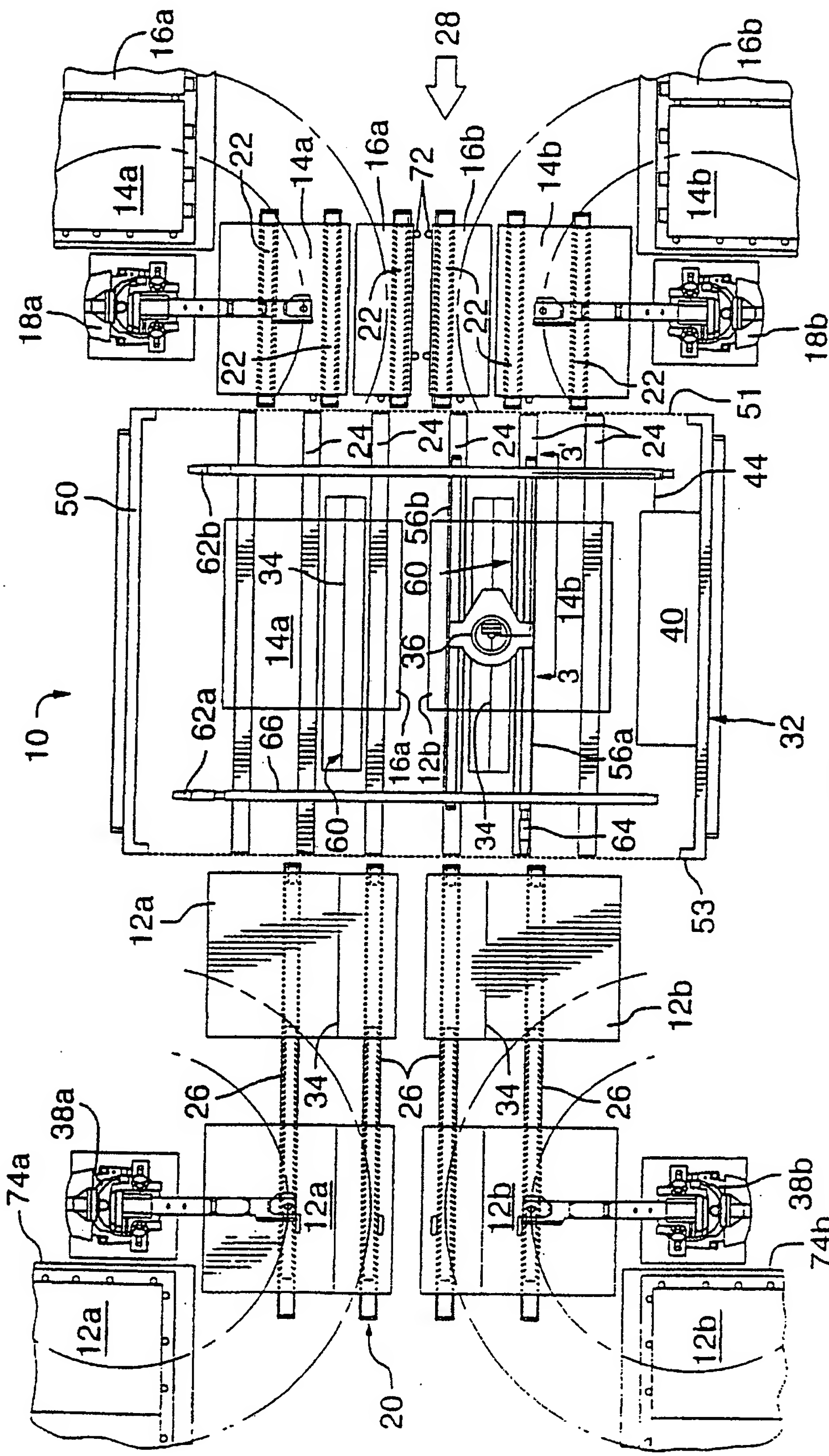

16a
28
16b
14a
22
14a
16a
72
16b
14b
14b
18a
18b
51
24
3'
44
50
62b
34
56b
60
14a
36
14b
3
40
10
62a
66
16a
12b
56a
32
60
34
64
53
12a
12b
34
26
34
26
38a
74a
12a
12b
38b
74b
20

FIG.1

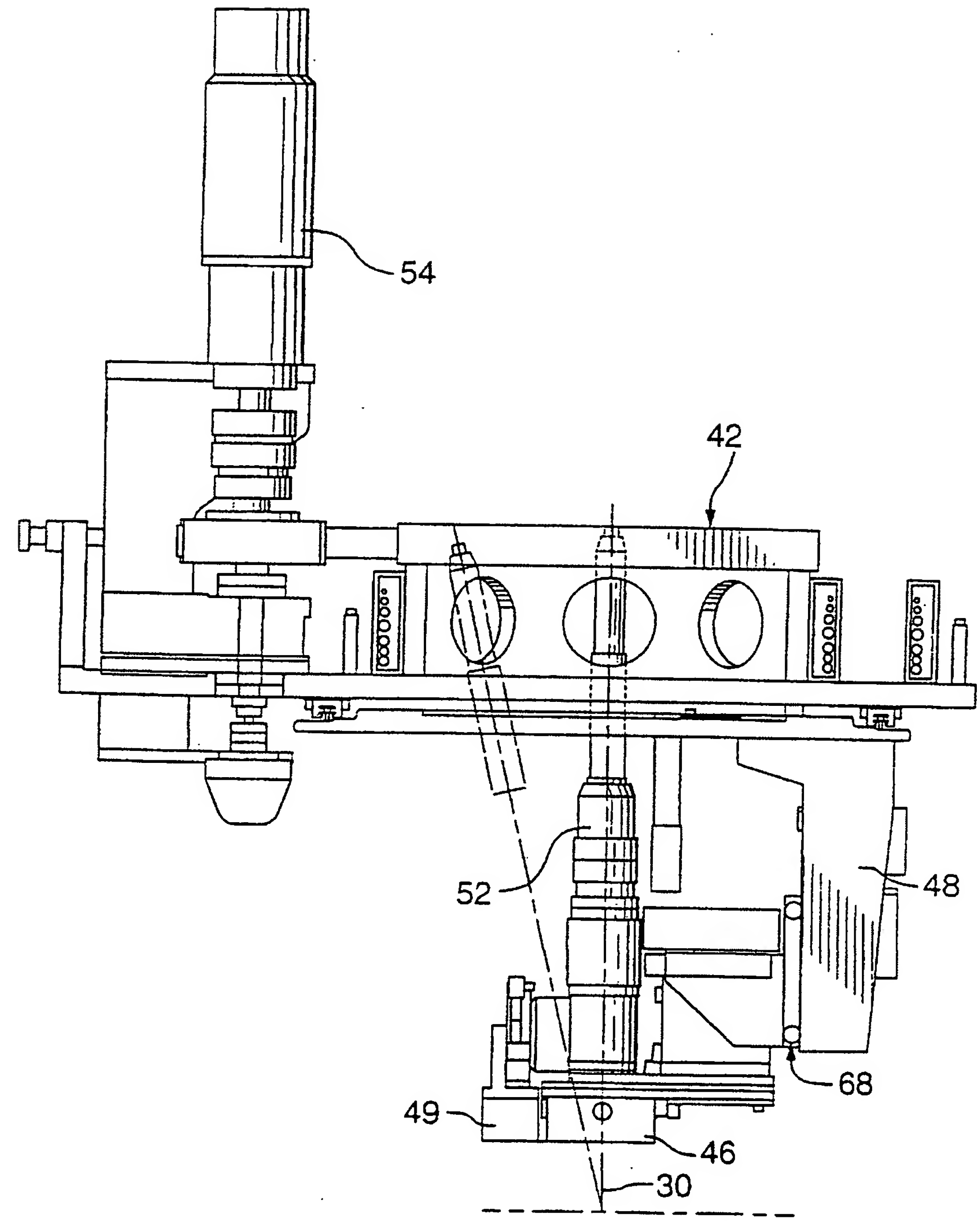


FIG.2

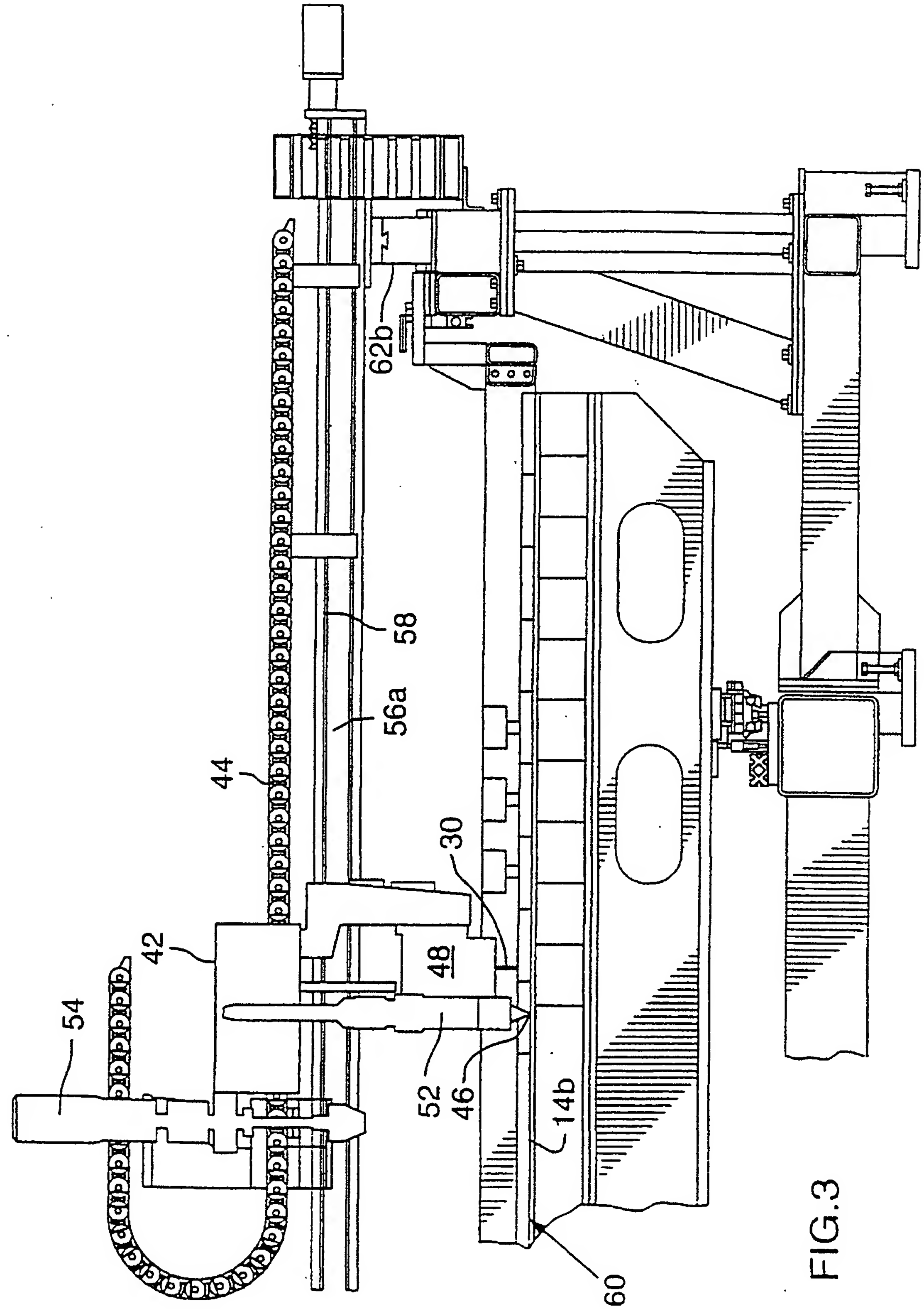
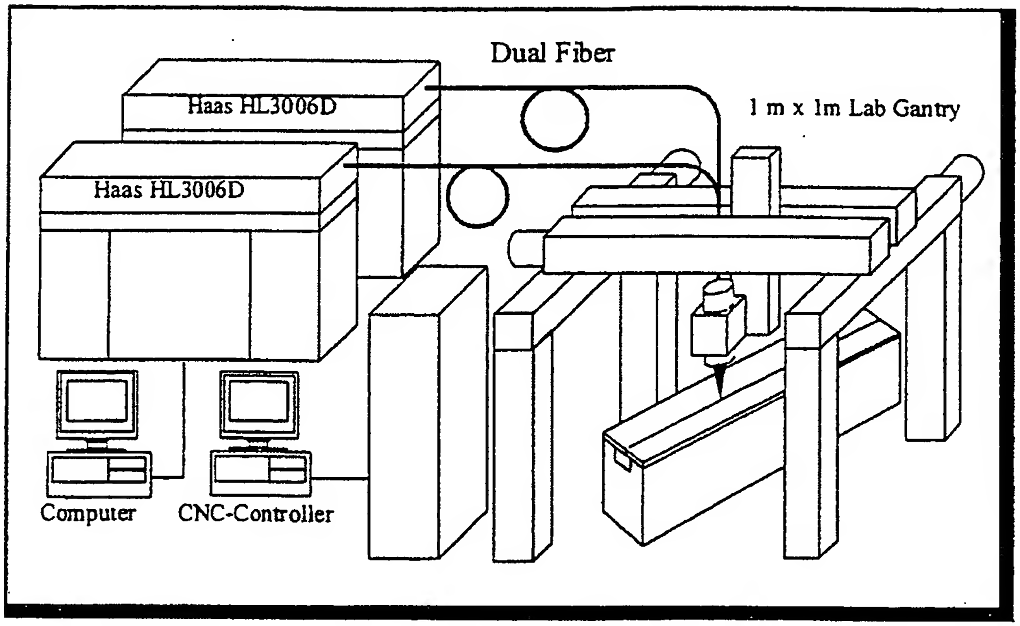


FIG.3

FIG. 4



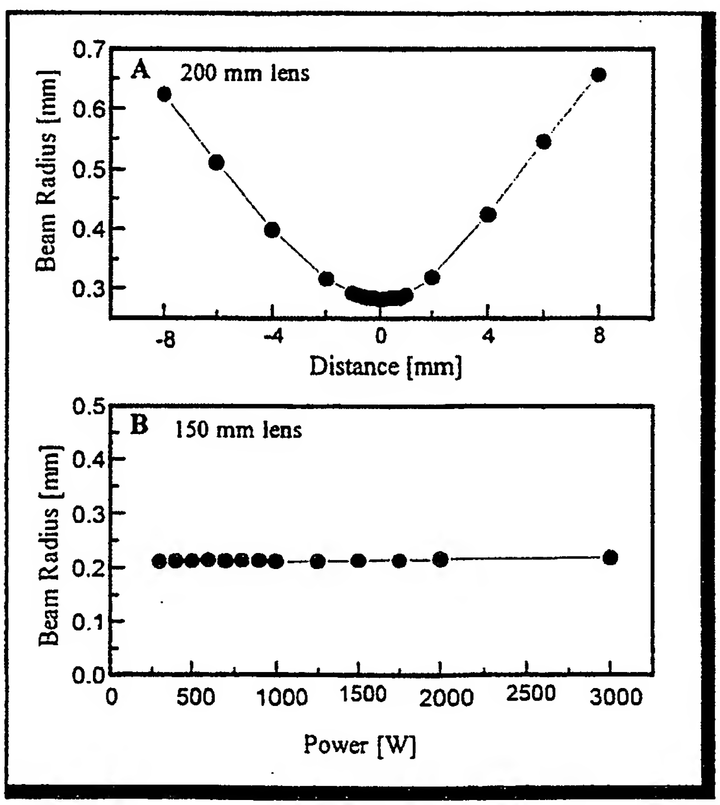


FIG. 5a

FIG. 5b

FIG. 6

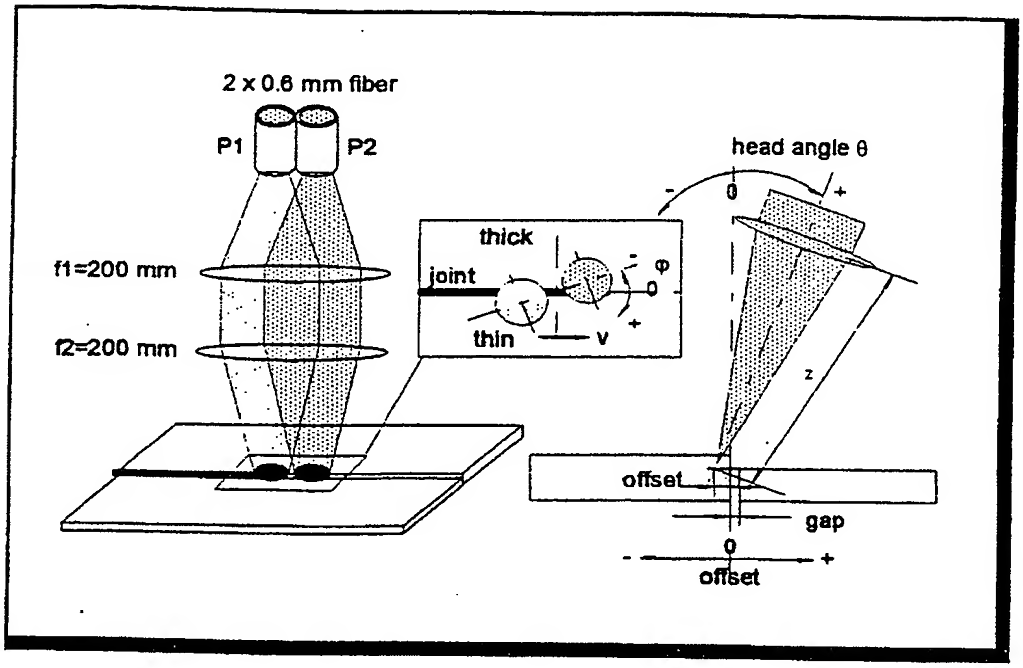

2 x 0.6 mm fiber
P1
P2
f1=200 mm
f2=200 mm
thick
joint
thin
v
φ
head angle θ
z
offset
gap
offset

FIG. 7

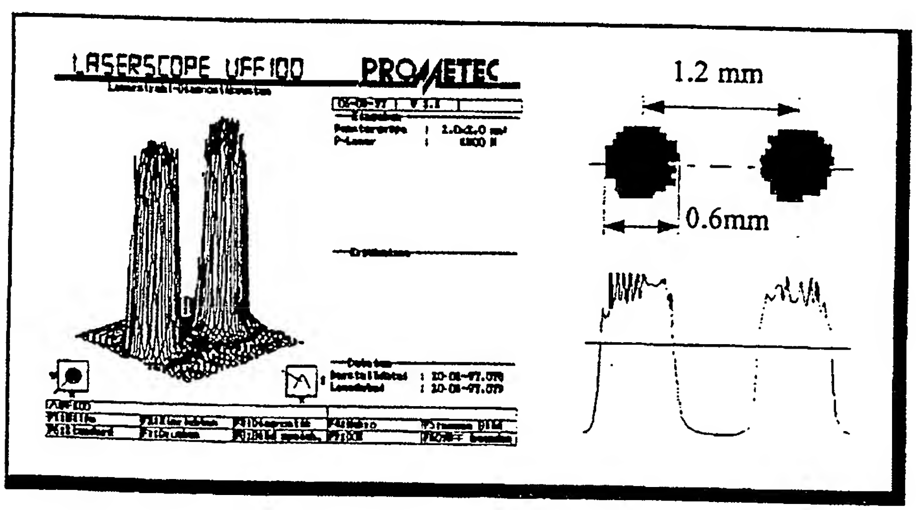

LASERSCOPE UFF100
PROMETEC
1.2 mm
0.6mm

FIG. 8

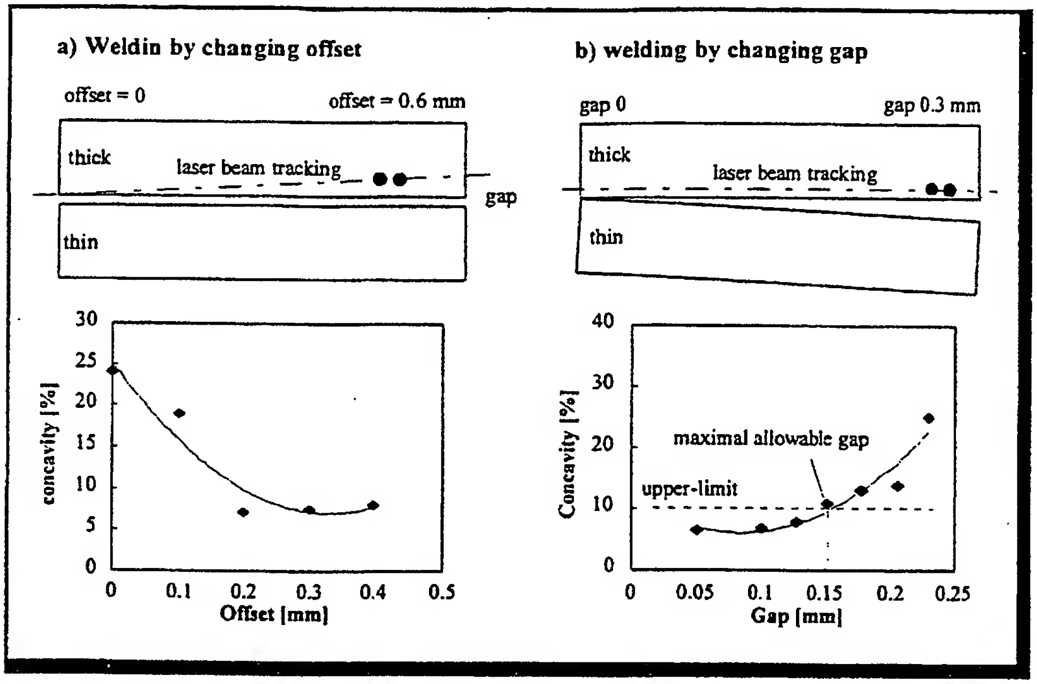

a) Weldin by changing offset
offset = 0
offset = 0.6 mm
thick
laser beam tracking
gap
thin
concavity [%]
Offset [mm]
b) welding by changing gap
gap 0
gap 0.3 mm
thick
laser beam tracking
thin
Concavity [%]
maximal allowable gap
upper-limit
Gap [mm]

FIG. 9

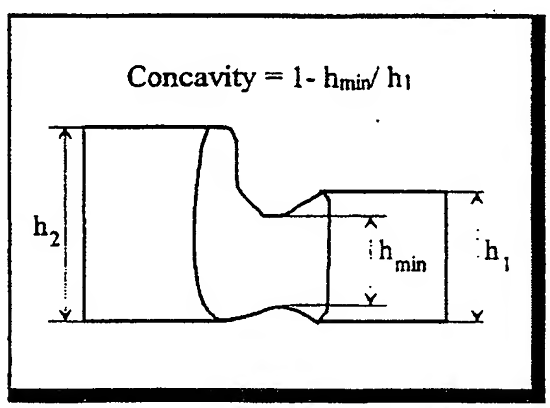

Concavity = 1- hmin/ h1
h2
h min
h1

FIG. 10

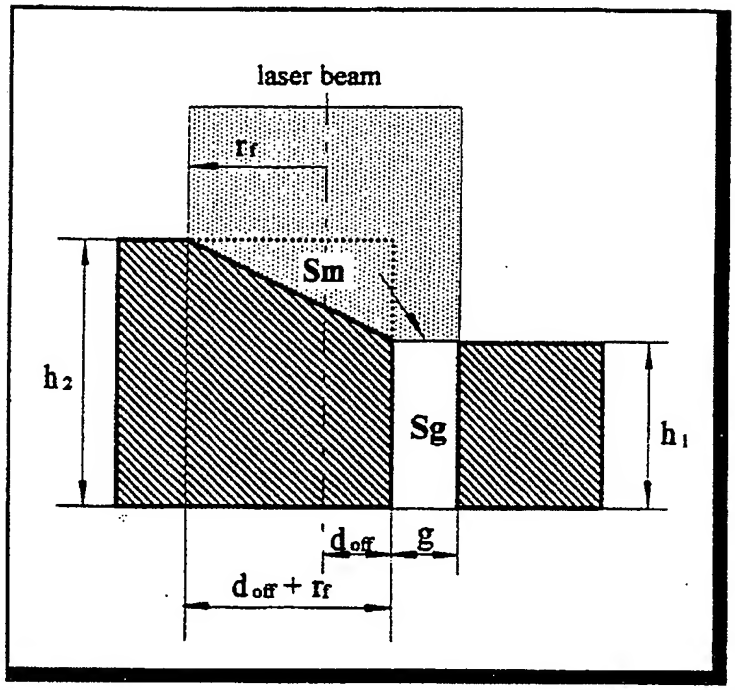
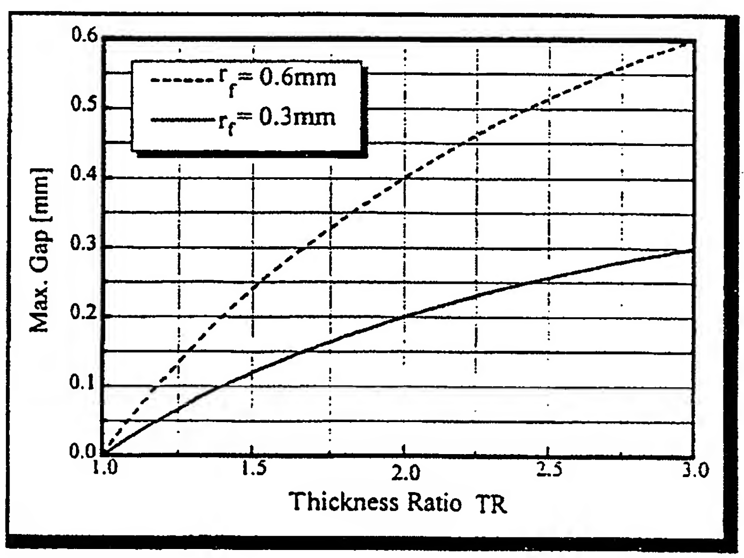

laser beam
r_f
Sm
h_2
Sg
h_1
d_{off}
g
$d_{off} + r_f$

FIG. 11


r_f = 0.6mm
r_f = 0.3mm
Max. Gap [mm]
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.0
1.5
2.0
2.5
3.0
Thickness Ratio TR

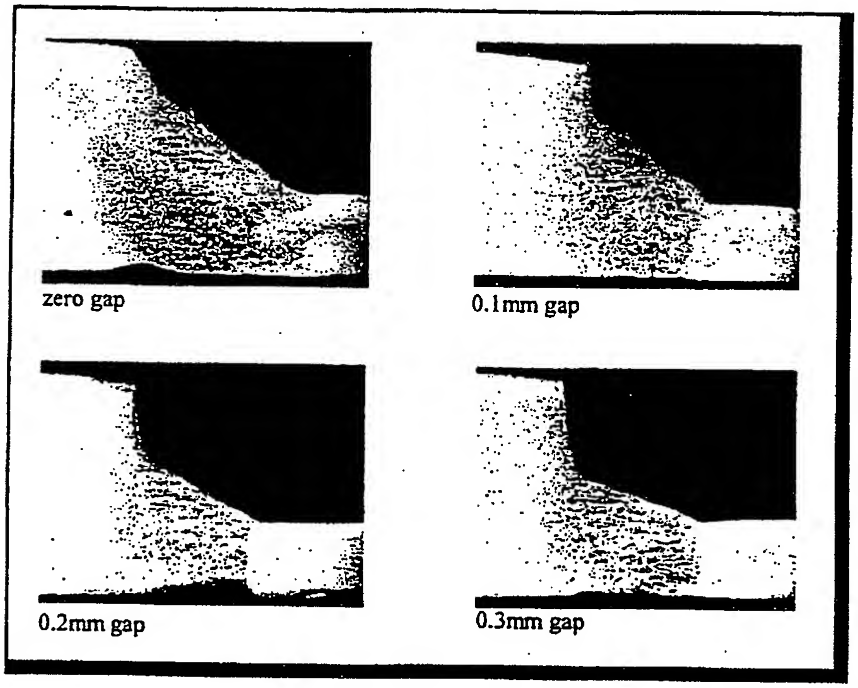

zero gap
0.1mm gap
0.2mm gap
0.3mm gap

FIG. 12

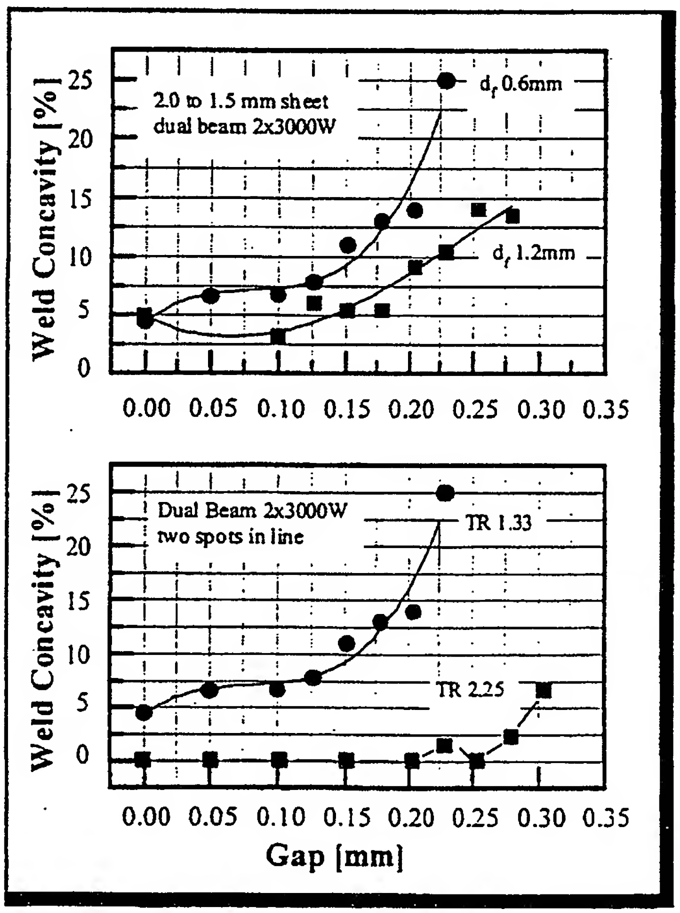

Weld Concavity [%]
2.0 to 1.5 mm sheet
dual beam 2x3000W
d_f 0.6mm
d_f 1.2mm
Dual Beam 2x3000W
two spots in line
TR 1.33
TR 2.25
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
Gap [mm]

FIG. 13

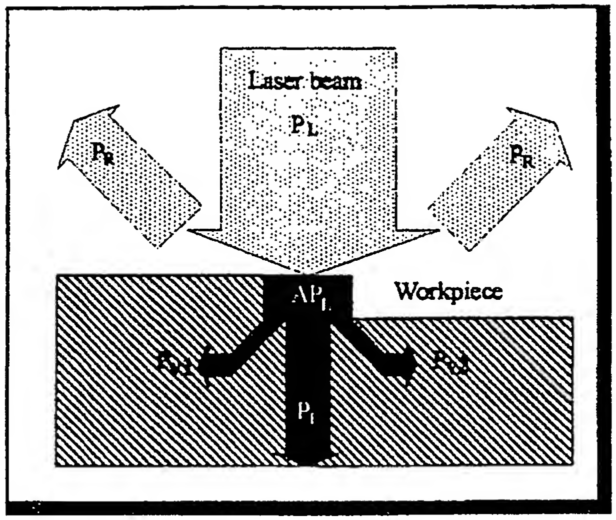


FIG. 14

FIG. 15

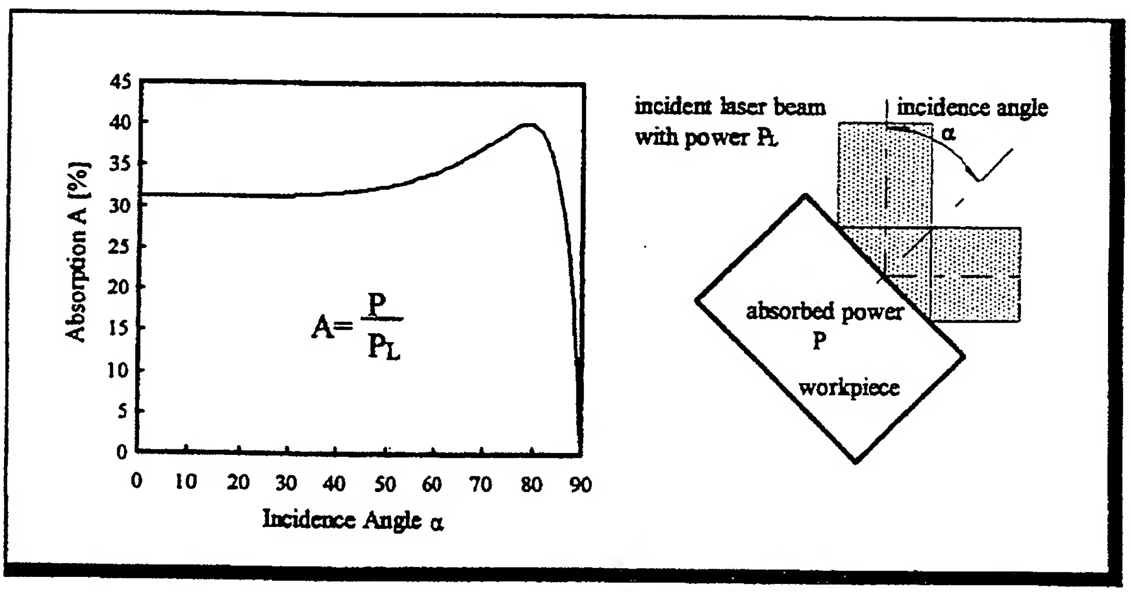


FIG. 16

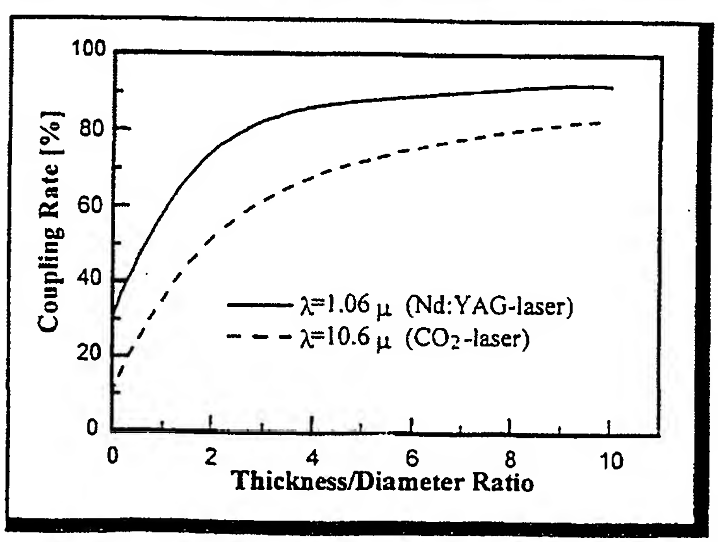


FIG. 17

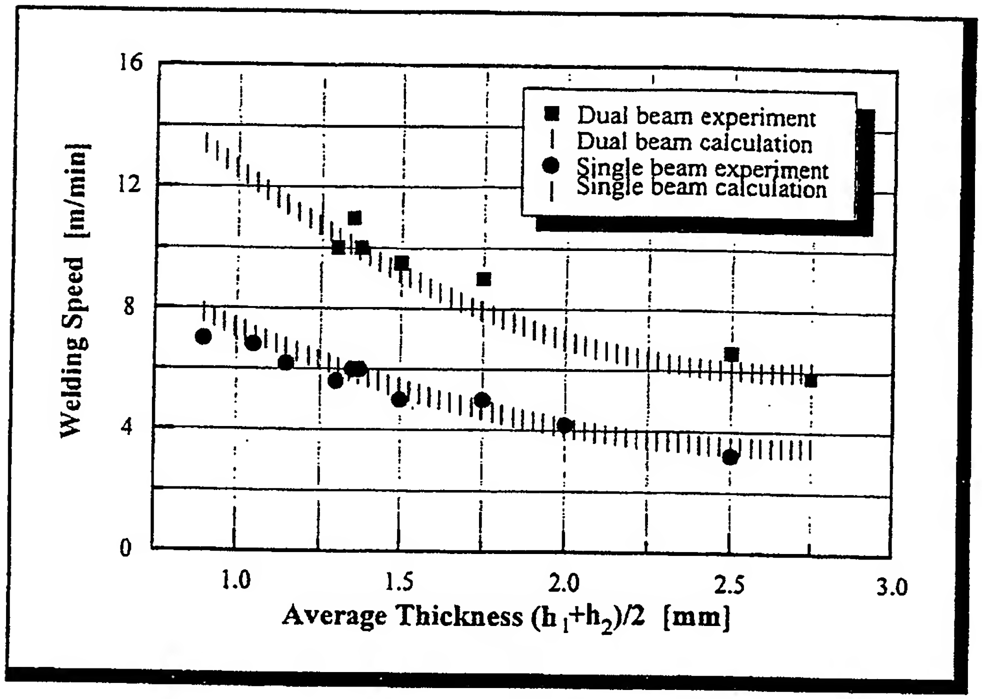

Welding Speed [m/min]
16
12
8
4
0
1.0
1.5
2.0
2.5
3.0
Average Thickness $(h_1+h_2)/2$ [mm]
Dual beam experiment
Dual beam calculation
Single beam experiment
Single beam calculation

FIG. 18

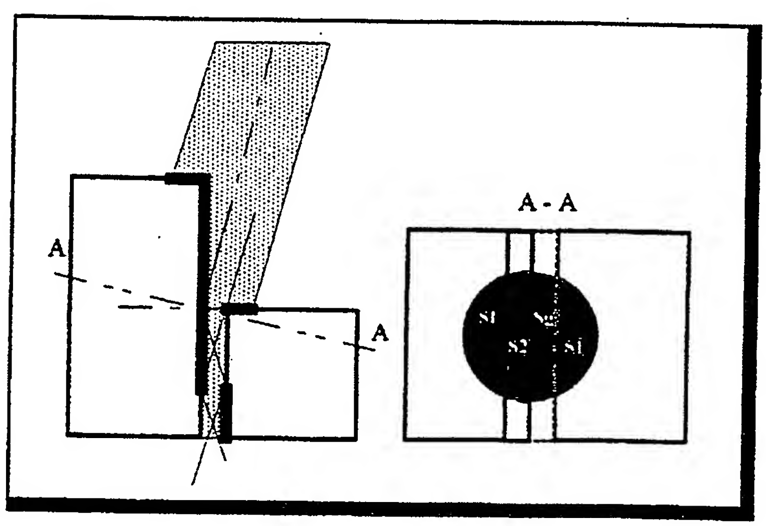

A
A
A - A
S1
S2
S1

FIG. 19

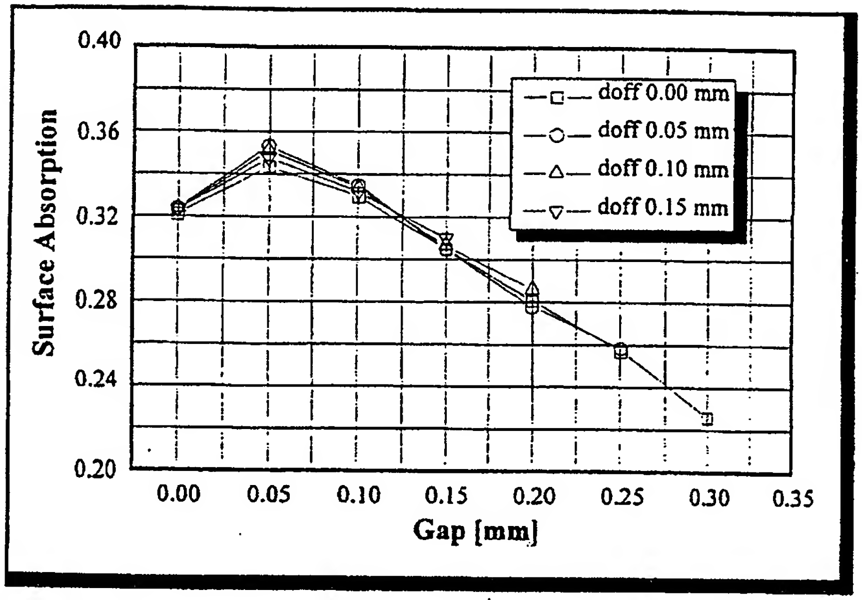

0.40
0.36
0.32
0.28
0.24
0.20
Surface Absorption
doff 0.00 mm
doff 0.05 mm
doff 0.10 mm
doff 0.15 mm
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Gap [mm]

FIG. 20

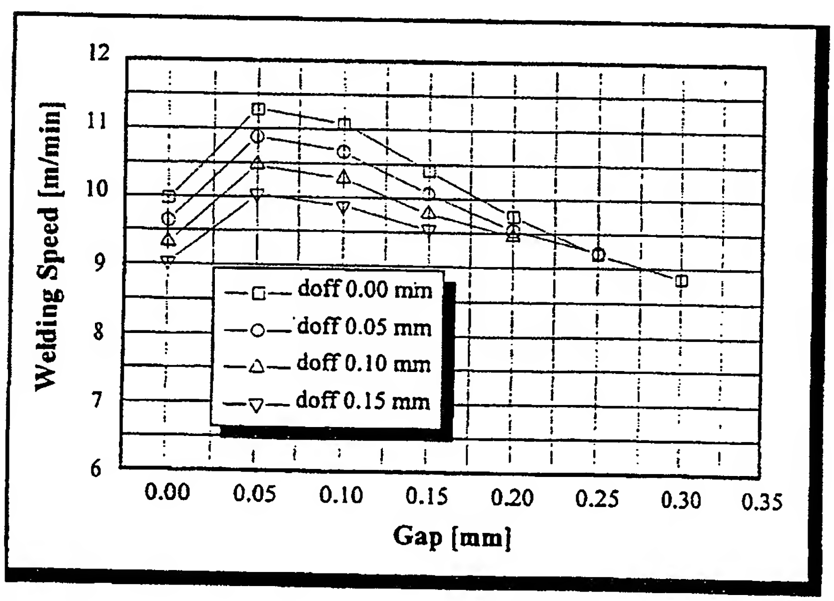

12
11
10
9
8
7
6
Welding Speed [m/min]
doff 0.00 mm
doff 0.05 mm
doff 0.10 mm
doff 0.15 mm
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Gap [mm]

FIG. 21

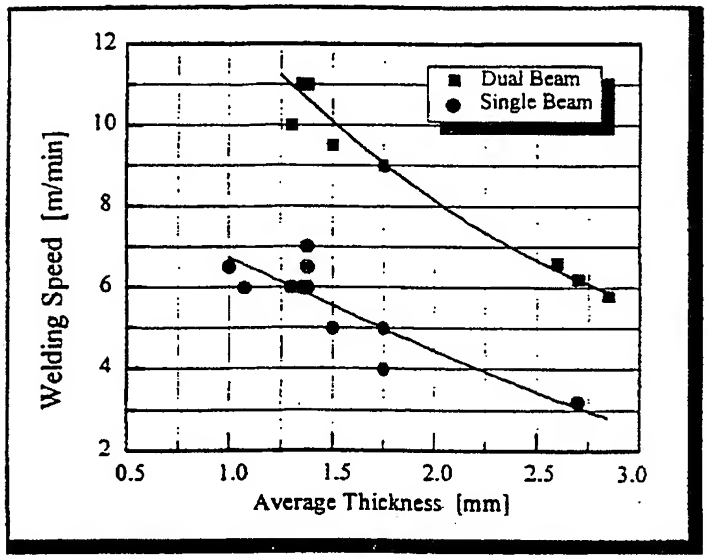
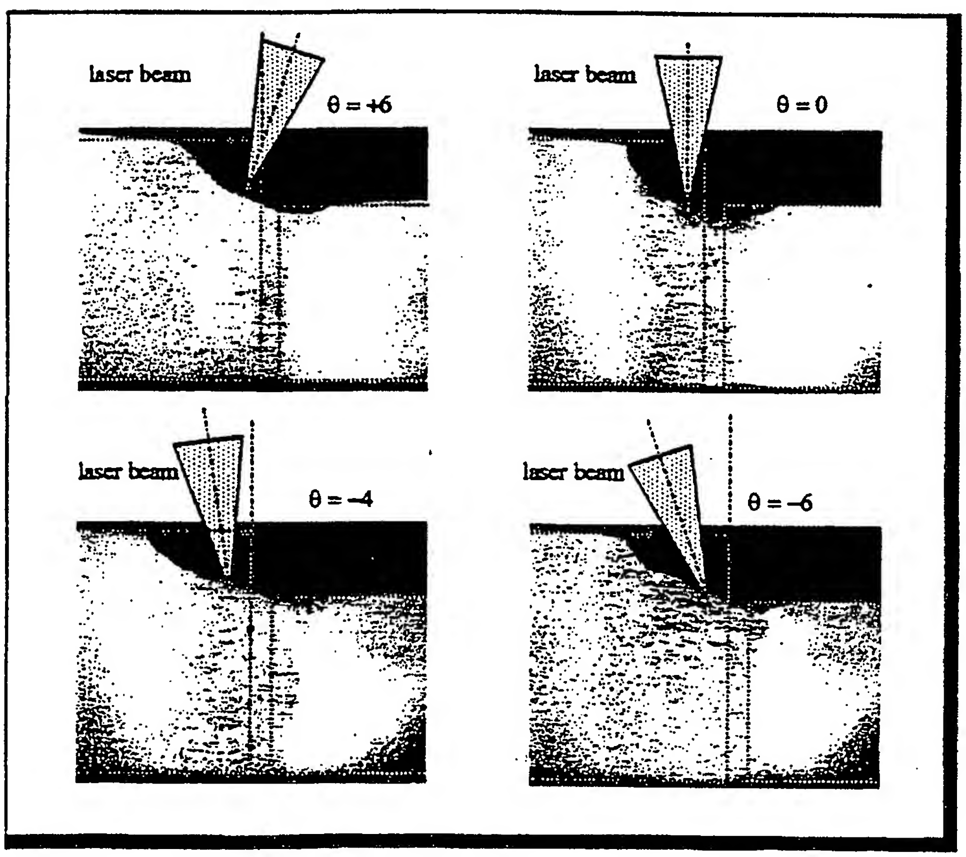

Dual Beam
Single Beam
Welding Speed [m/min]
12
10
8
6
4
2
0.5
1.0
1.5
2.0
2.5
3.0
Average Thickness [mm]

FIG. 22


laser beam
θ = +6
laser beam
θ = 0
laser beam
θ = −4
laser beam
θ = −6

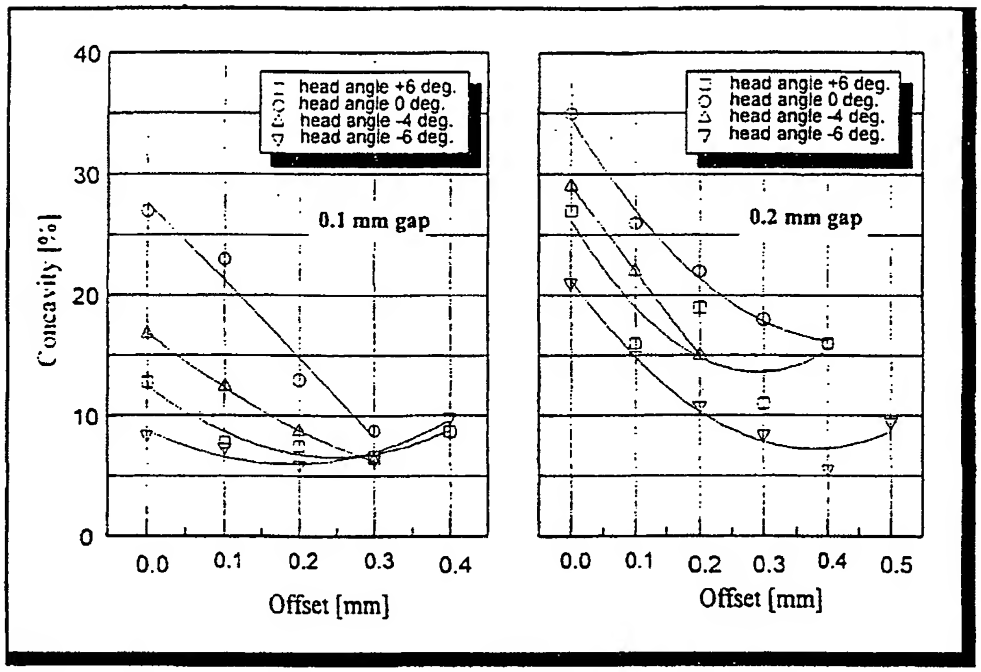


FIG. 23

FIG. 24

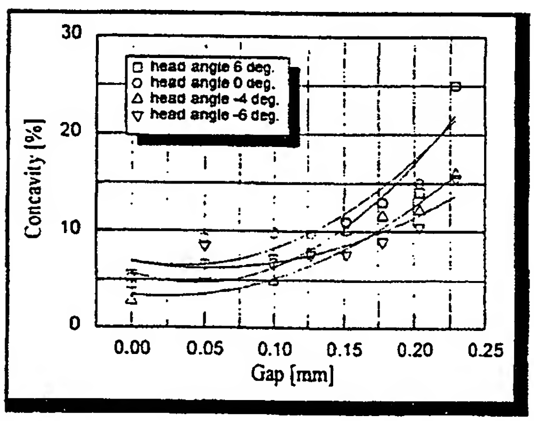
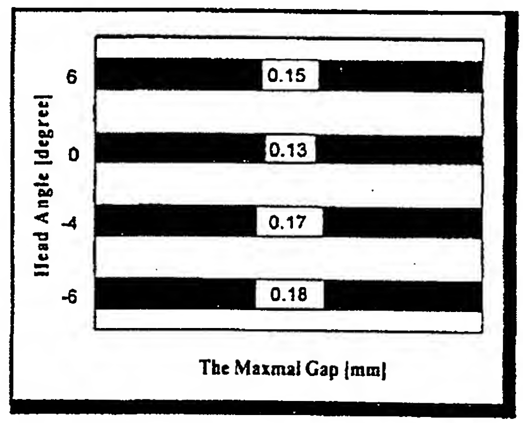


FIG. 25



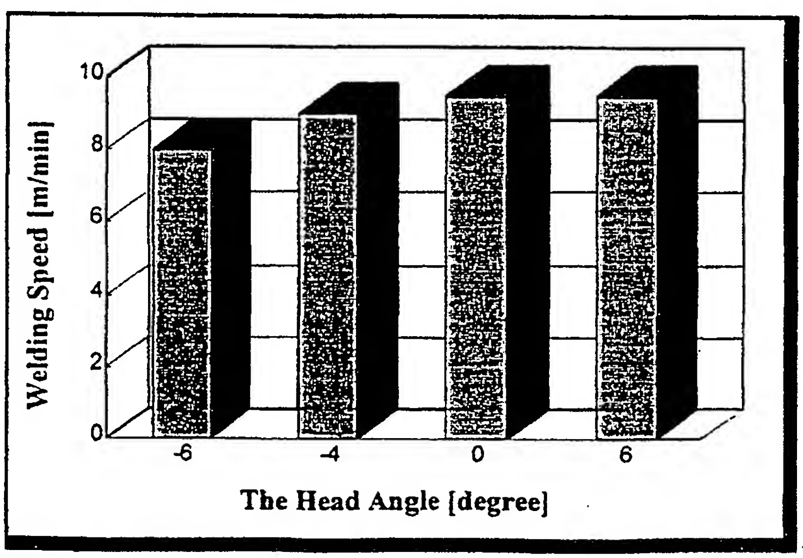


FIG. 26

FIG. 27

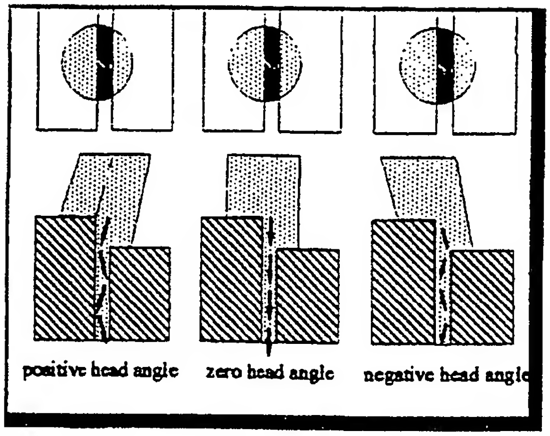


FIG. 28

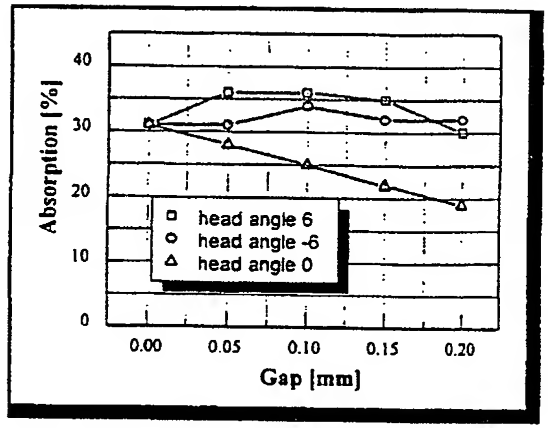


FIG. 29

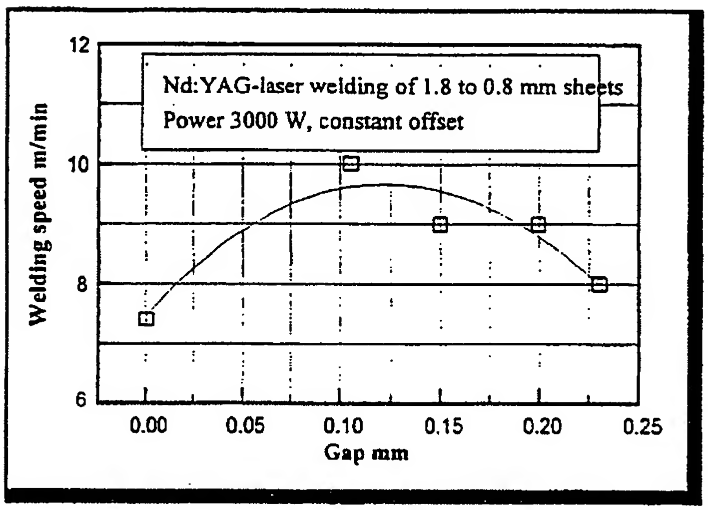
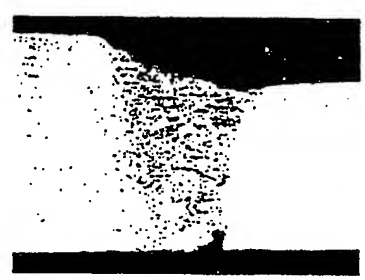


FIG. 30

A. welding with proper offset

B. welding with too small offset



C. Welding with too large offset

FIG. 31

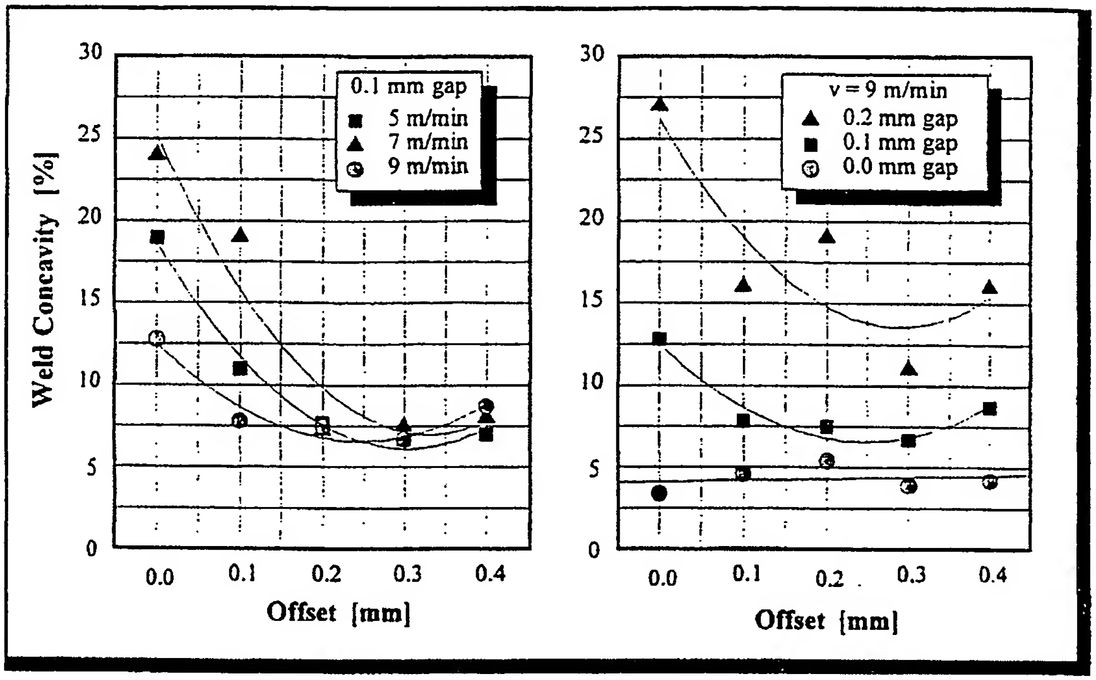

Weld Concavity [%]
0.1 mm gap
5 m/min
7 m/min
9 m/min
Offset [mm]
v = 9 m/min
0.2 mm gap
0.1 mm gap
0.0 mm gap
Offset [mm]

FIG. 32

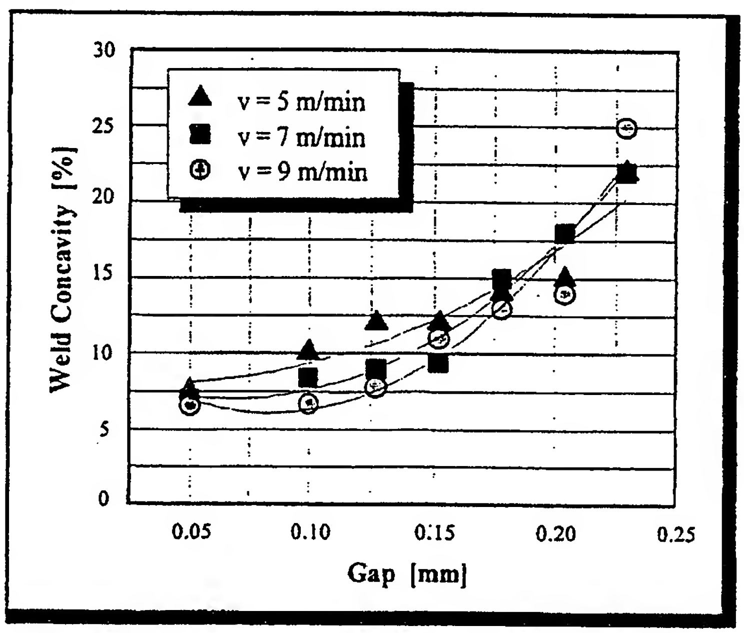

Weld Concavity [%]
v = 5 m/min
v = 7 m/min
v = 9 m/min
Gap [mm]

FIG. 33

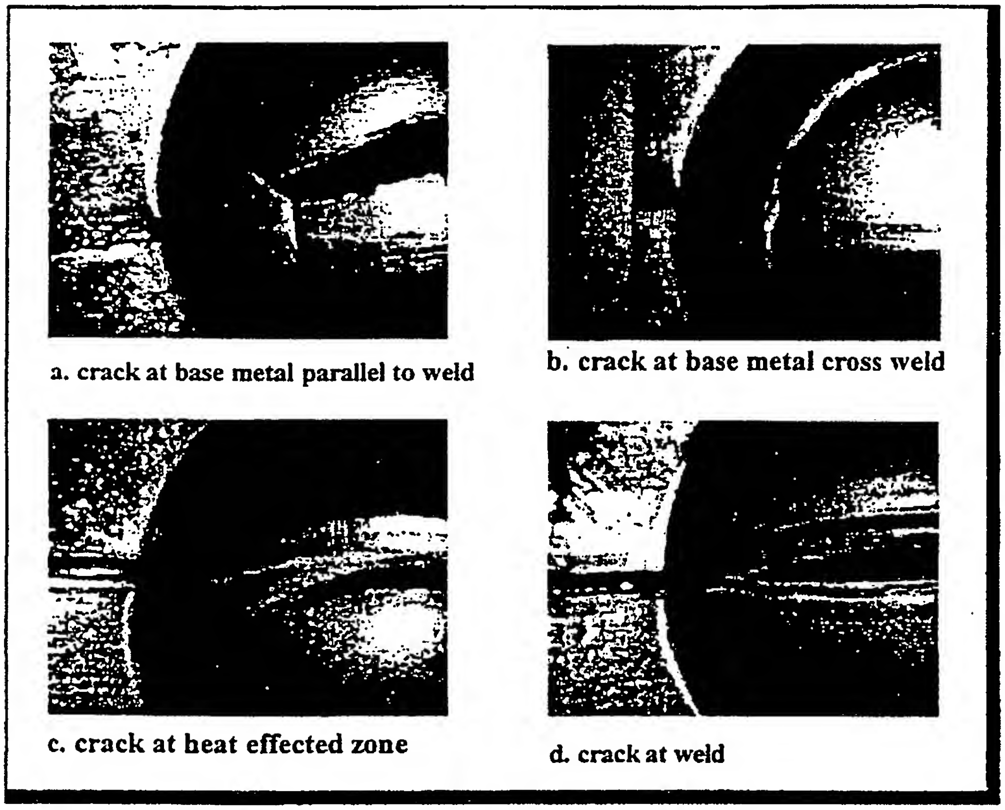
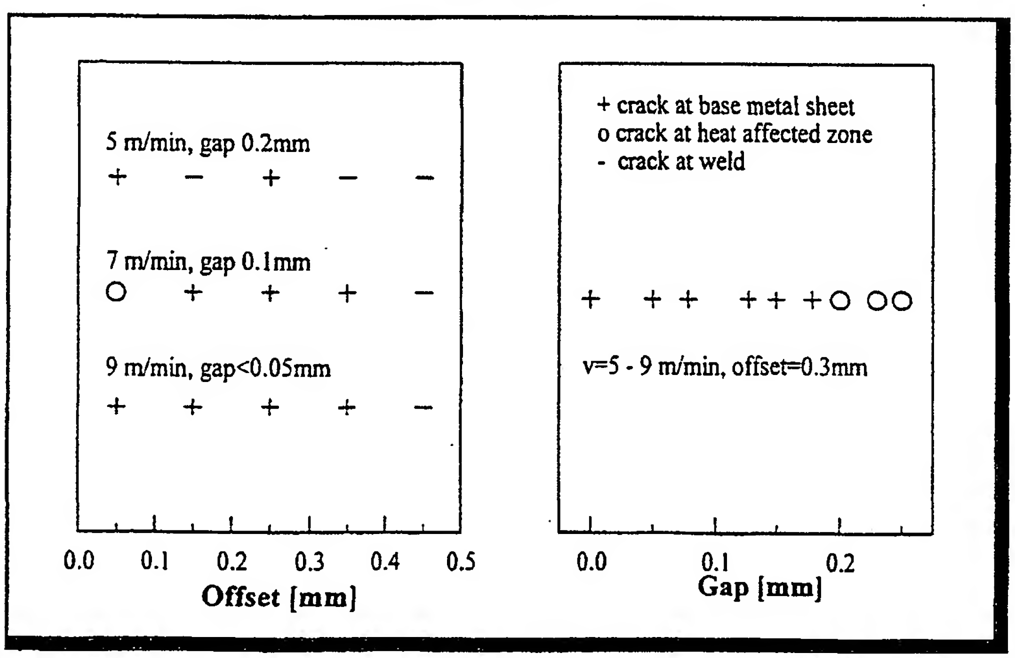

a. crack at base metal parallel to weld
b. crack at base metal cross weld
c. crack at heat effected zone
d. crack at weld

FIG. 34


5 m/min, gap 0.2mm
7 m/min, gap 0.1mm
9 m/min, gap<0.05mm
0.0 0.1 0.2 0.3 0.4 0.5
Offset [mm]
+ crack at base metal sheet
o crack at heat affected zone
- crack at weld
v=5 - 9 m/min, offset=0.3mm
0.0 0.1 0.2
Gap [mm]

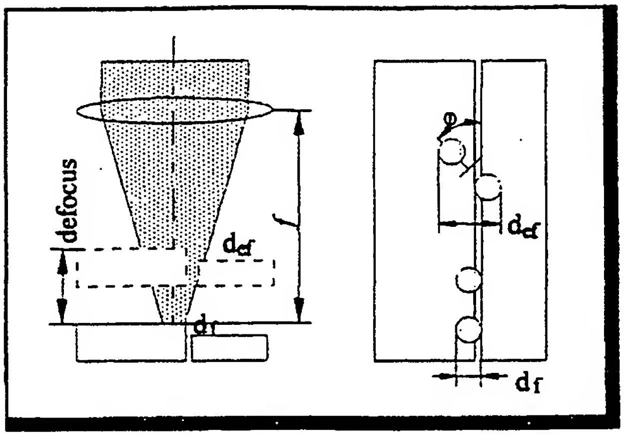
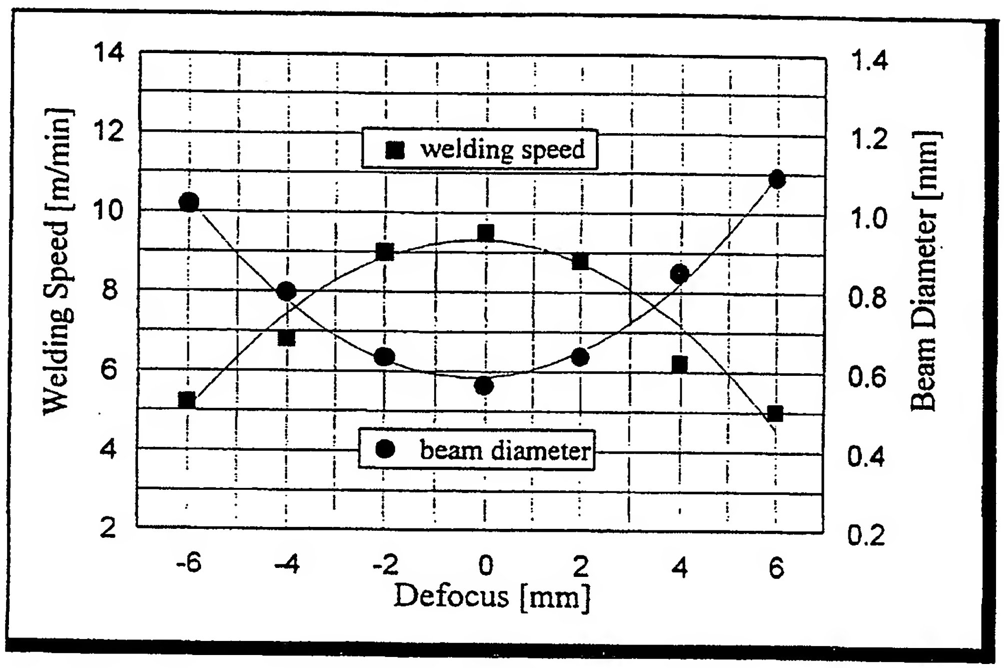


FIG. 35

FIG. 36



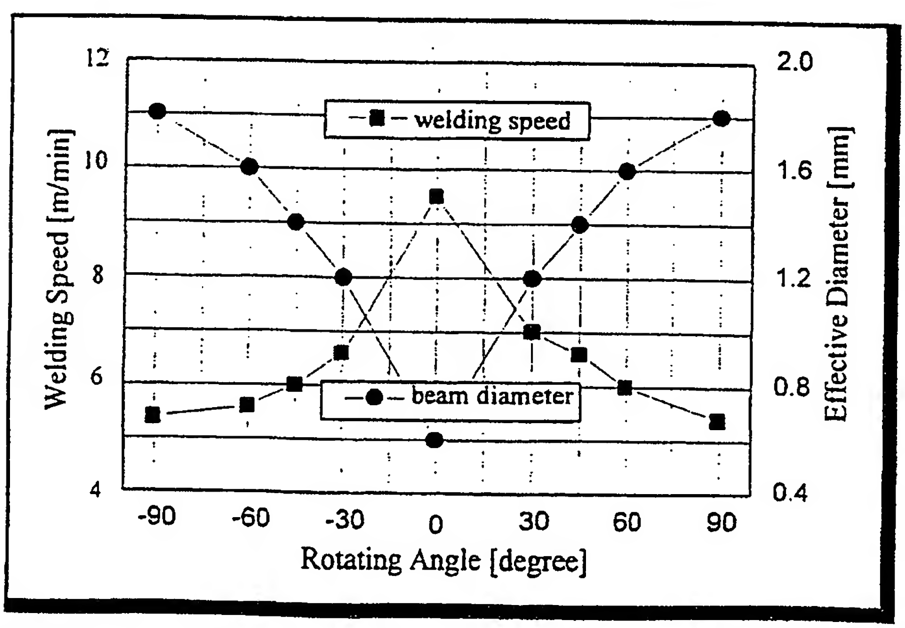


FIG. 37

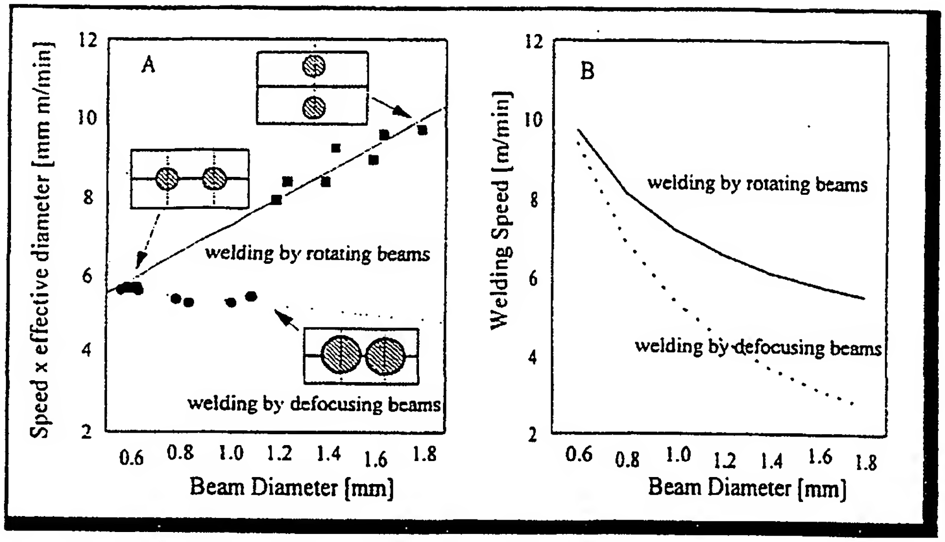


FIG. 38

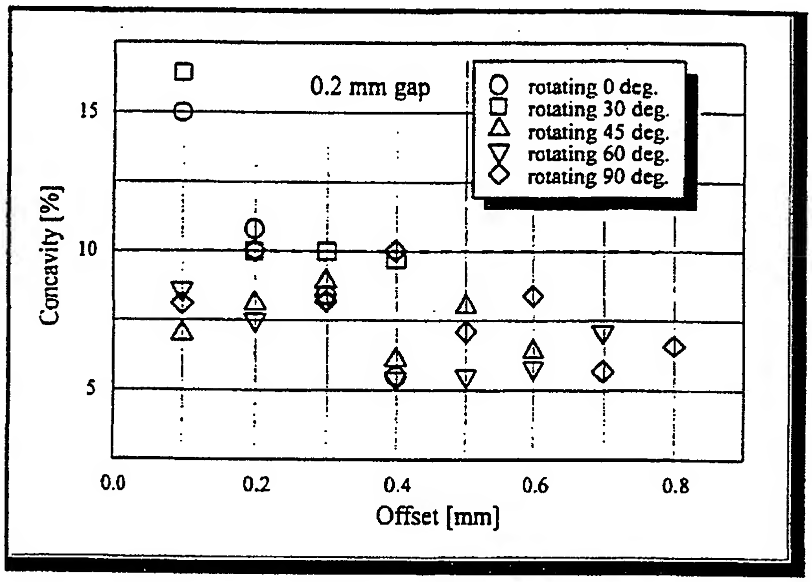


FIG. 40

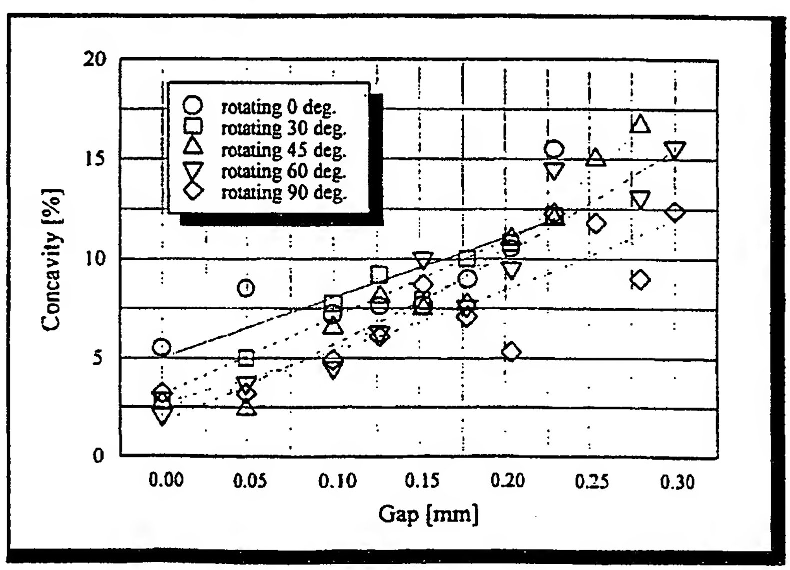


FIG. 41

FIG. 39

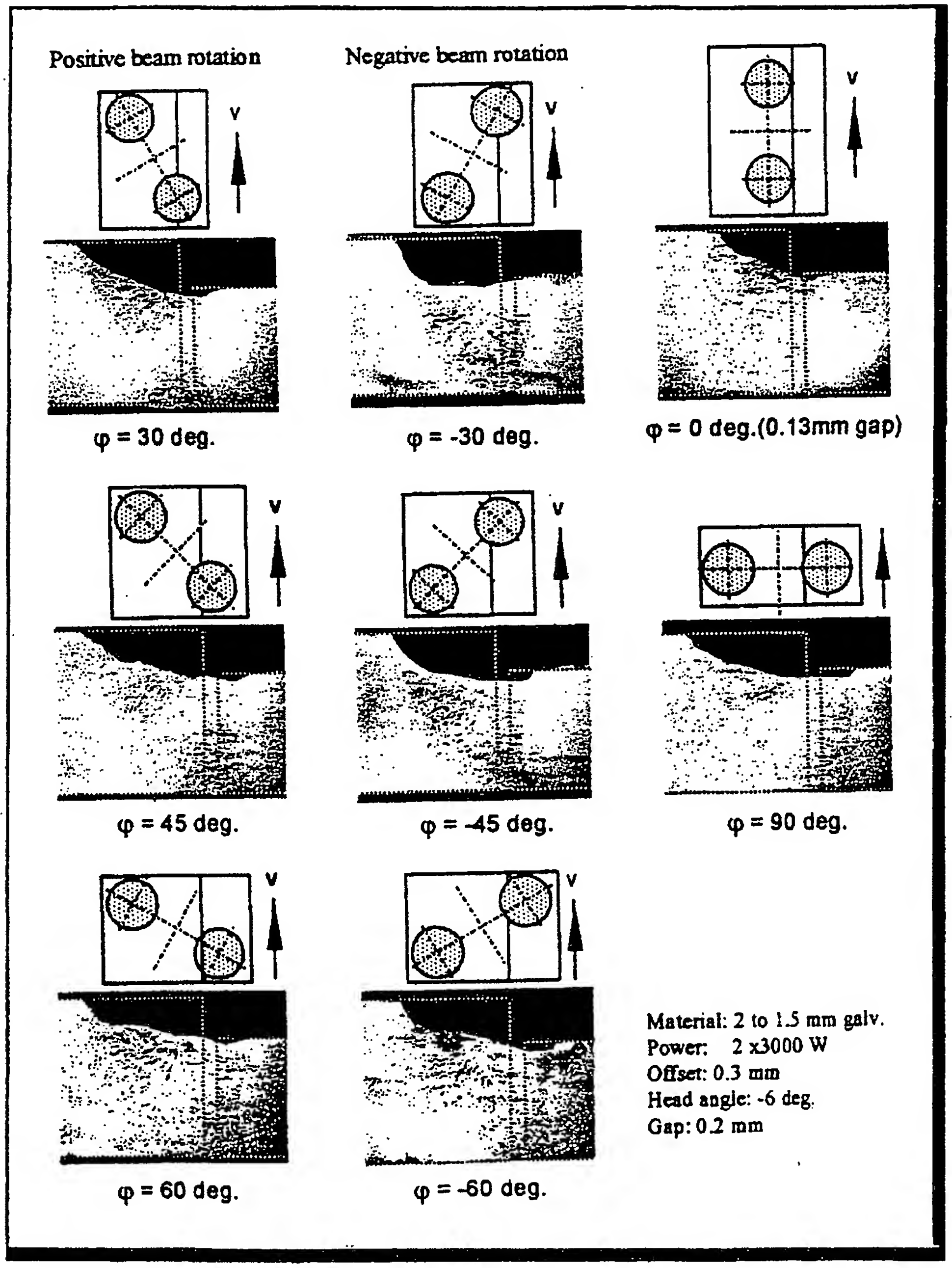

Positive beam rotation
Negative beam rotation
V
φ = 30 deg.
φ = -30 deg.
φ = 0 deg.(0.13mm gap)
φ = 45 deg.
φ = -45 deg.
φ = 90 deg.
φ = 60 deg.
φ = -60 deg.
Material: 2 to 1.5 mm galv.
Power: 2 x3000 W
Offset: 0.3 mm
Head angle: -6 deg.
Gap: 0.2 mm

FIG. 42

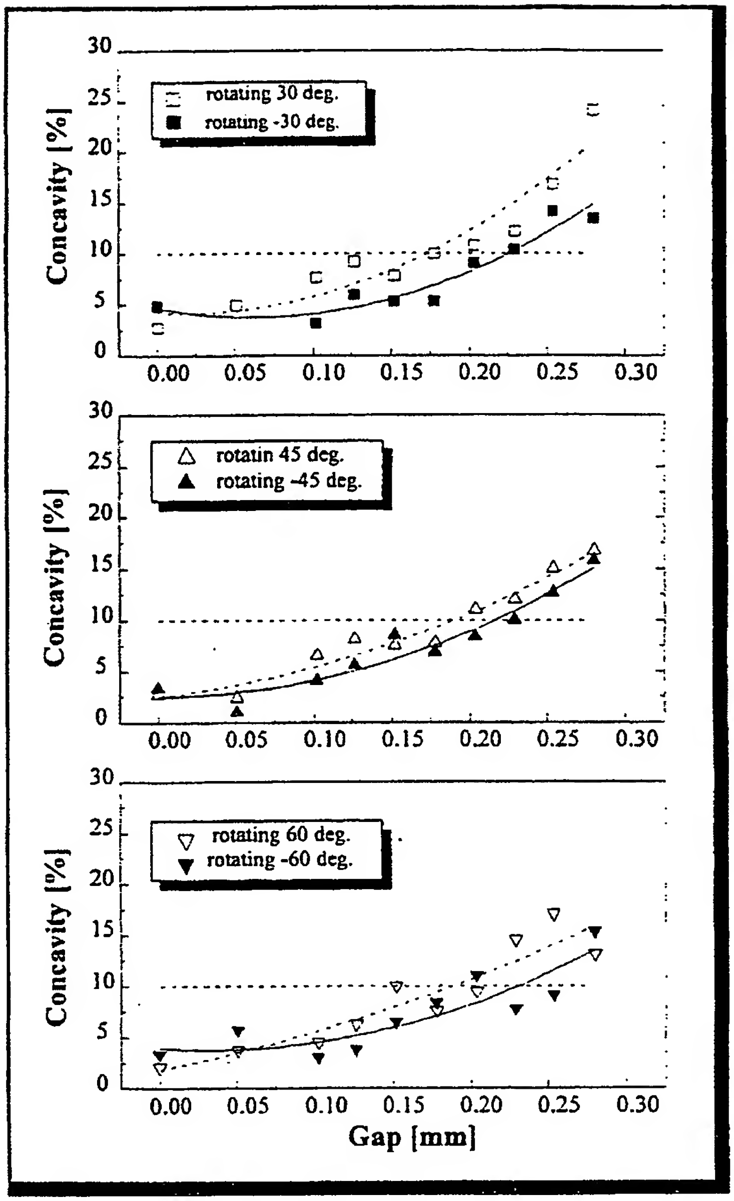

rotating 30 deg.
rotating -30 deg.
Concavity [%]
0
5
10
15
20
25
30
0.00
0.05
0.10
0.15
0.20
0.25
0.30
rotatin 45 deg.
rotating -45 deg.
Concavity [%]
rotating 60 deg.
rotating -60 deg.
Concavity [%]
Gap [mm]

FIG. 43

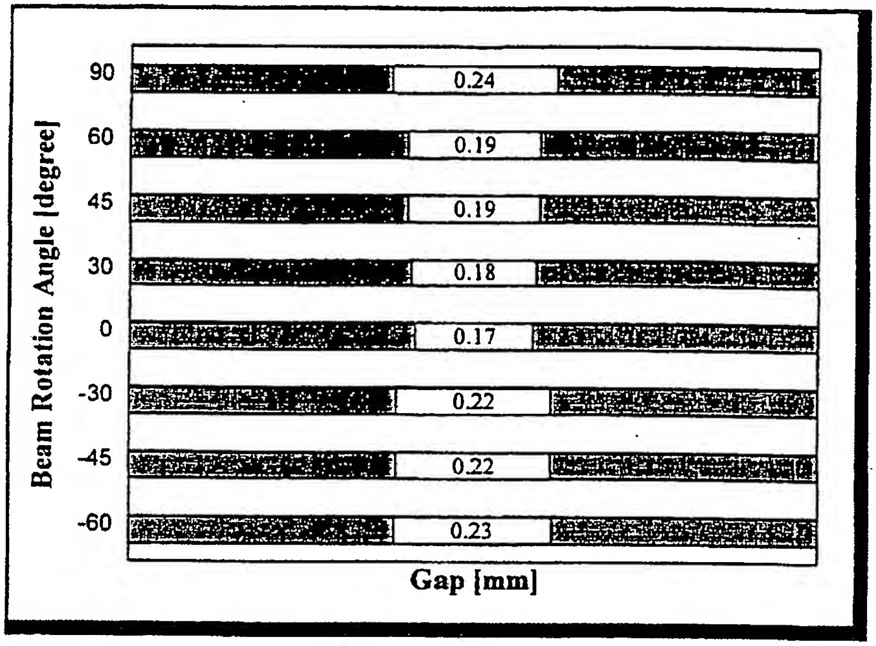
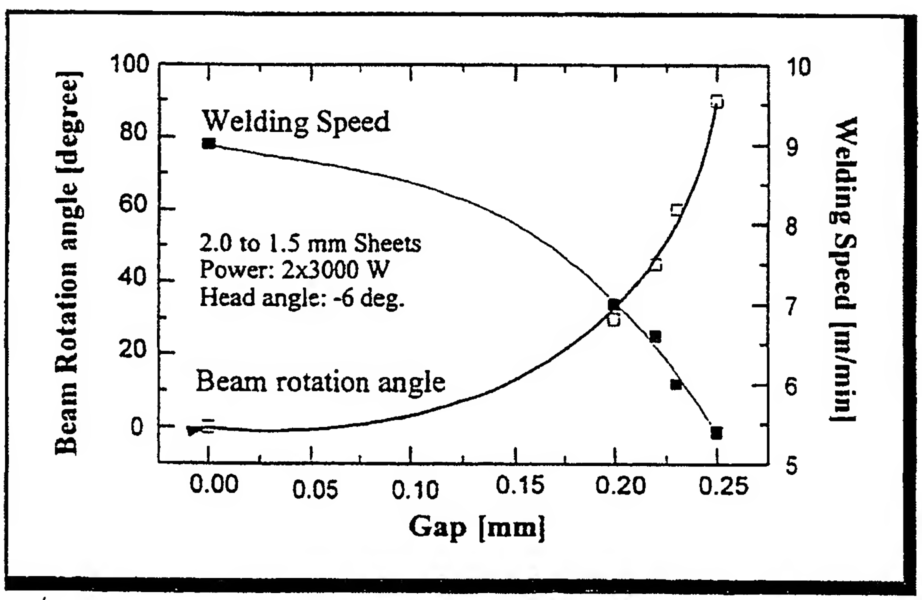

Beam Rotation Angle [degree]
90
60
45
30
0
-30
-45
-60
0.24
0.19
0.19
0.18
0.17
0.22
0.22
0.23
Gap [mm]

FIG. 44


Beam Rotation angle [degree]
100
80
60
40
20
0
Welding Speed
2.0 to 1.5 mm Sheets
Power: 2x3000 W
Head angle: -6 deg.
Beam rotation angle
0.00
0.05
0.10
0.15
0.20
0.25
Gap [mm]
10
9
8
7
6
5
Welding Speed [m/min]

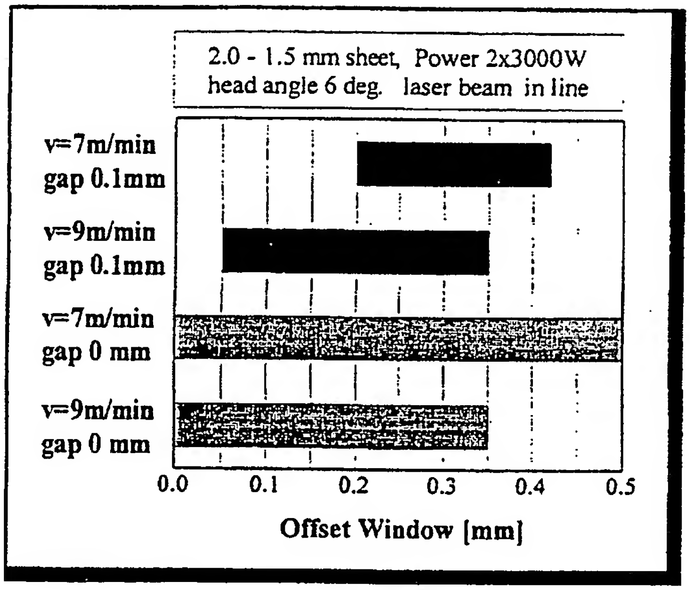


FIG. 45

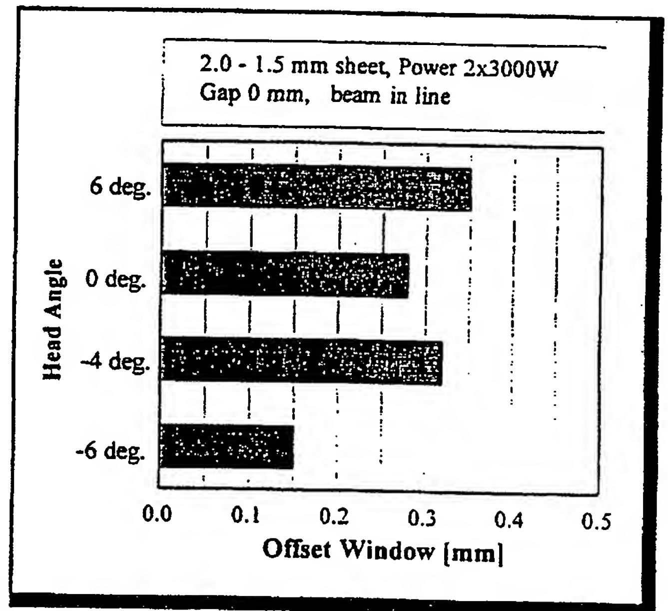


FIG. 46

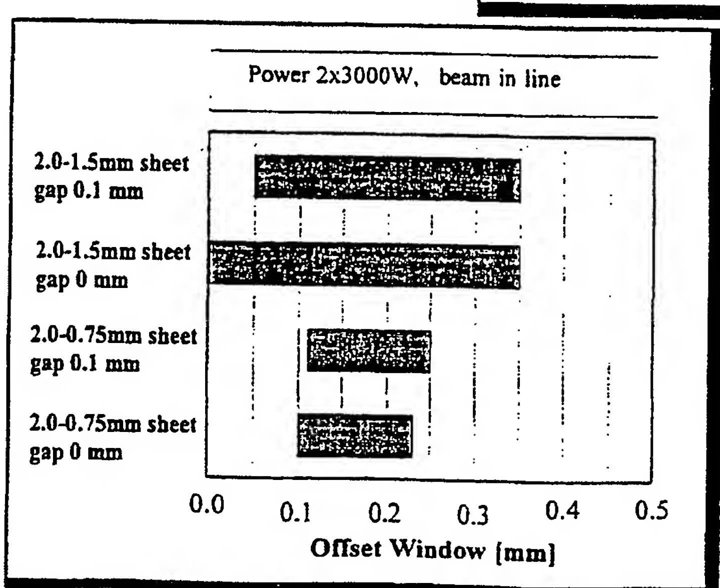


FIG. 47

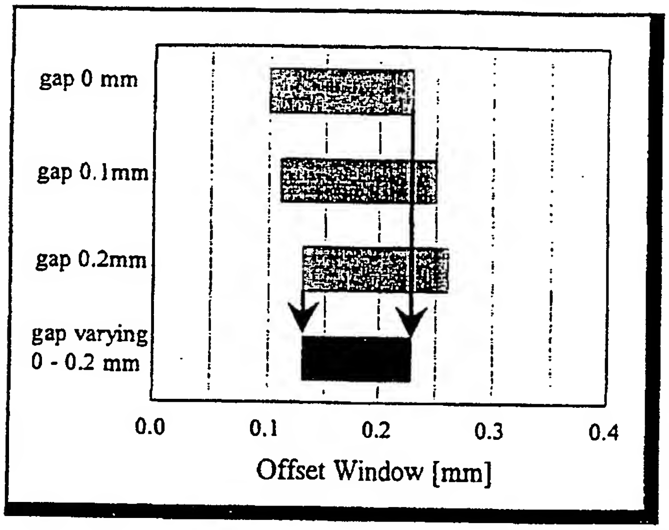


FIG. 48

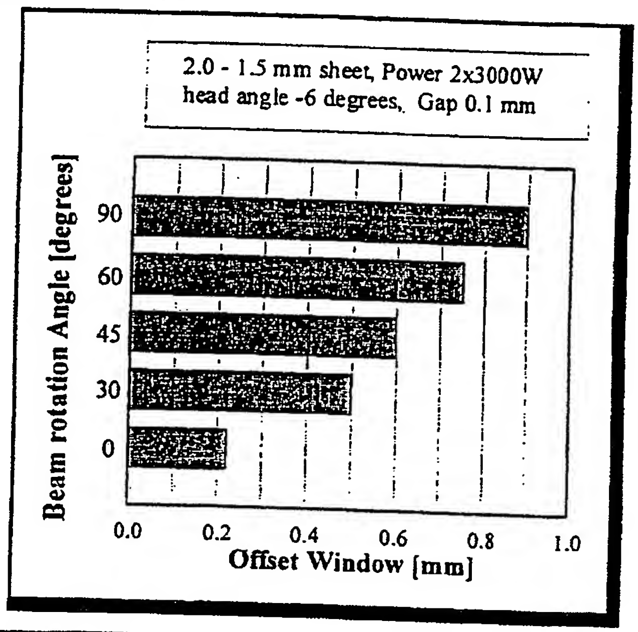


FIG. 49

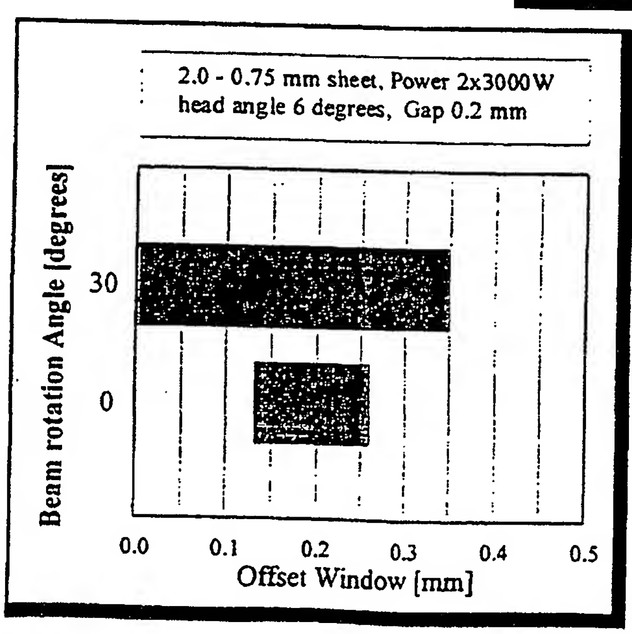


FIG. 50

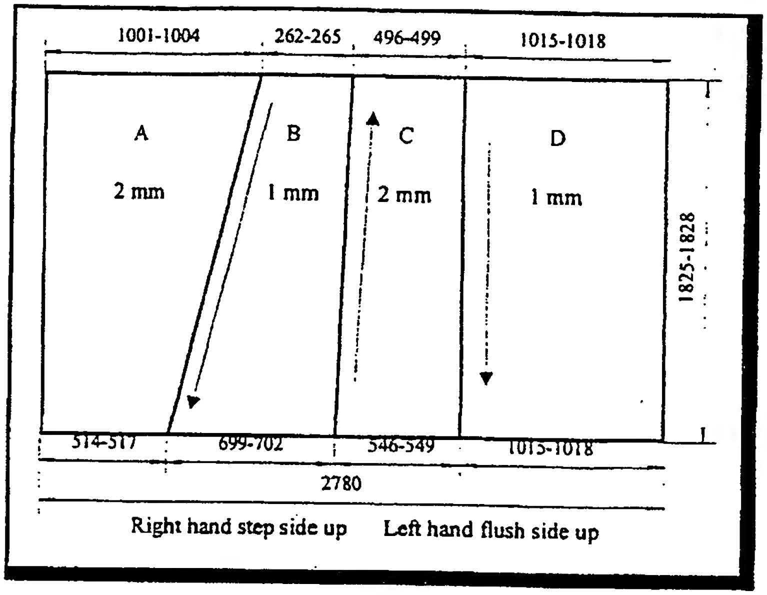
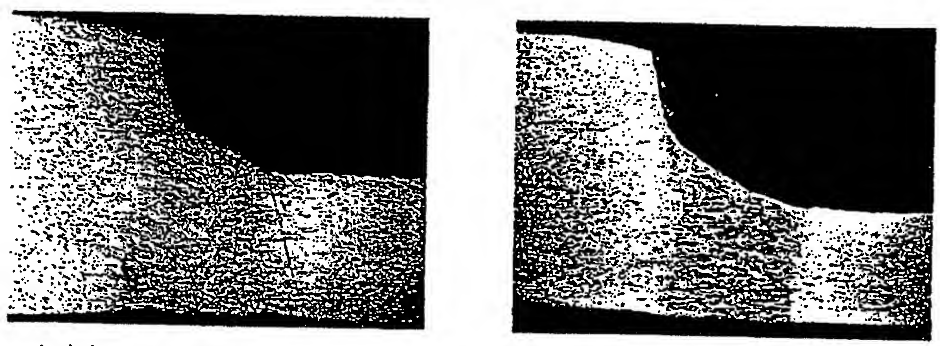


FIG. 51



a. single beam, 3000W, 5m/nin 200 mm focal lens

b. dual beam, 2x2800W, 9 m/min. 150 mm focal lens, 30 degrees beam rotation

FIG. 52

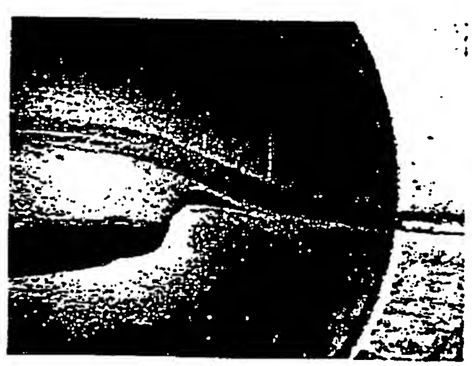
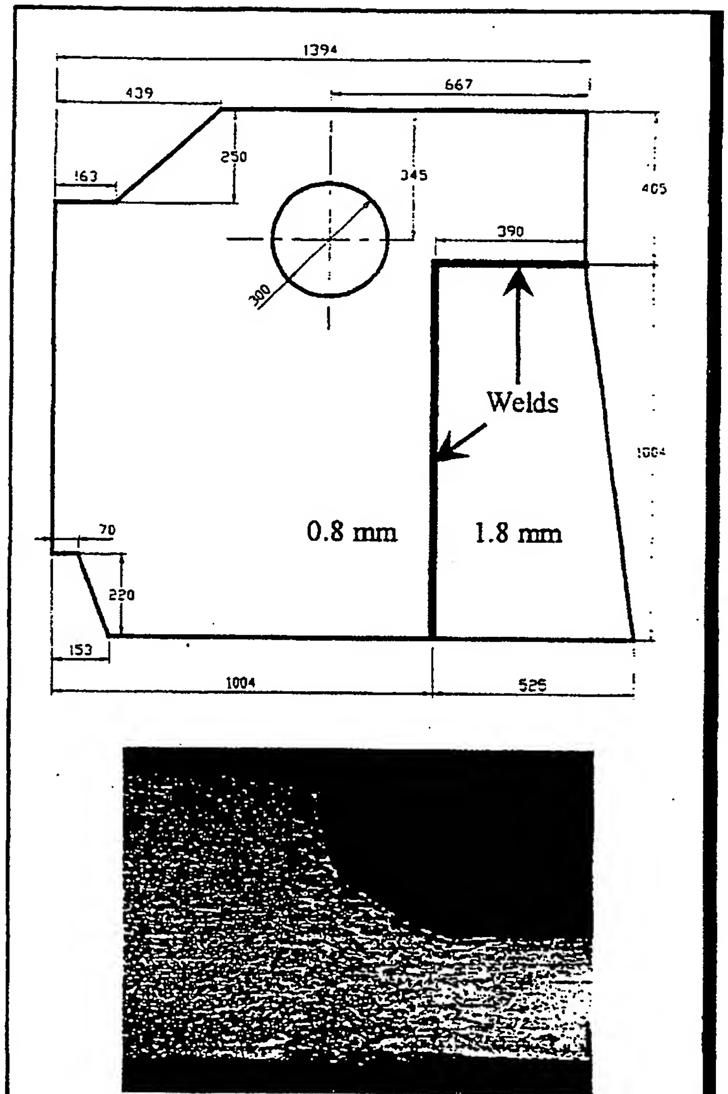
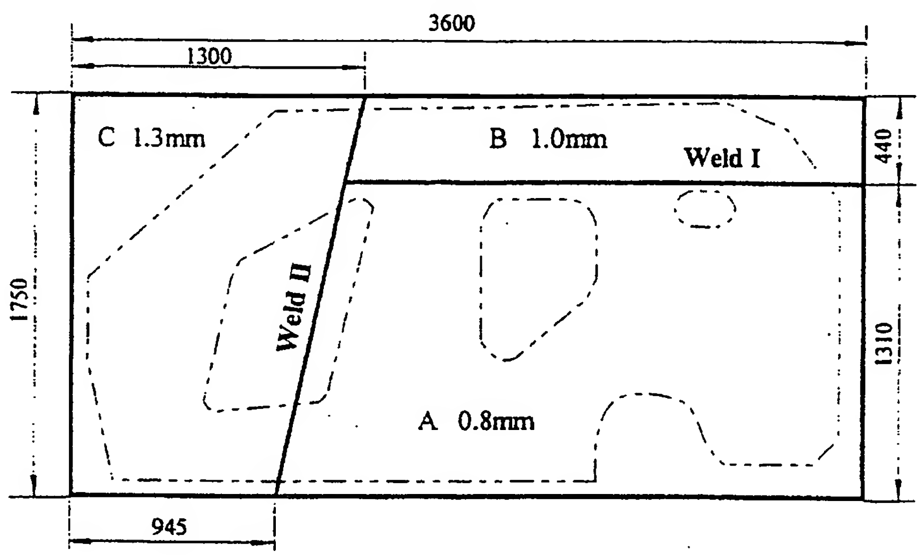


FIG. 53



weld cross section

FIG. 54



Procedure of the Welding Process

Weld I. Parts A to B
Shear the welded part AB to the required size
Weld II. Parts AB to C

FIG. 55

FIG. 56

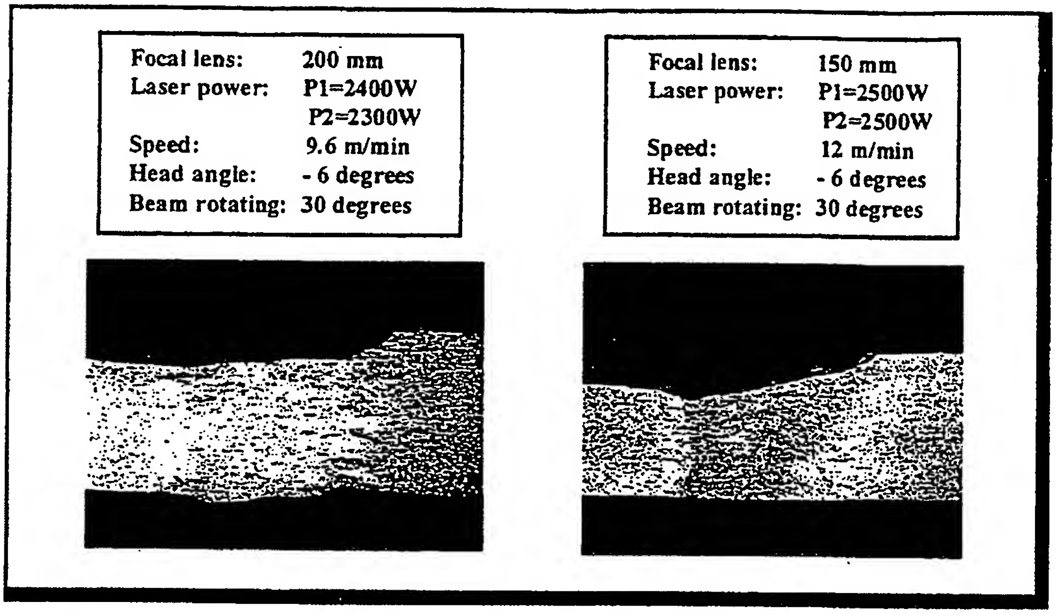

Focal lens: 200 mm
Laser power: P1=2400W
P2=2300W
Speed: 9.6 m/min
Head angle: - 6 degrees
Beam rotating: 30 degrees
Focal lens: 150 mm
Laser power: P1=2500W
P2=2500W
Speed: 12 m/min
Head angle: - 6 degrees
Beam rotating: 30 degrees

FIG. 57

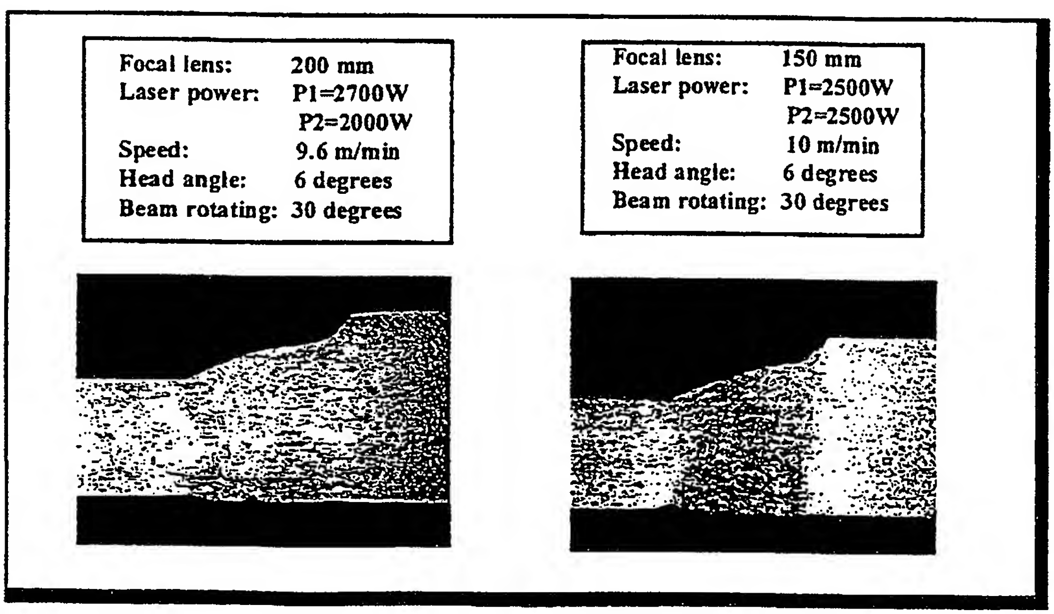

Focal lens: 200 mm
Laser power: P1=2700W
P2=2000W
Speed: 9.6 m/min
Head angle: 6 degrees
Beam rotating: 30 degrees
Focal lens: 150 mm
Laser power: P1=2500W
P2=2500W
Speed: 10 m/min
Head angle: 6 degrees
Beam rotating: 30 degrees

FIG. 58

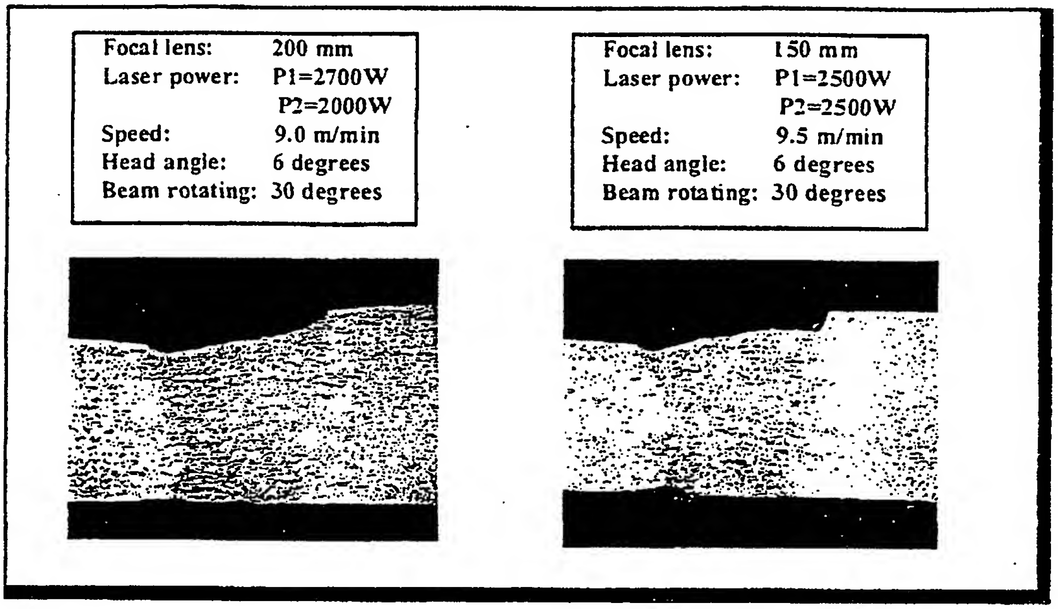

Focal lens: 200 mm
Laser power: P1=2700W
P2=2000W
Speed: 9.0 m/min
Head angle: 6 degrees
Beam rotating: 30 degrees
Focal lens: 150 mm
Laser power: P1=2500W
P2=2500W
Speed: 9.5 m/min
Head angle: 6 degrees
Beam rotating: 30 degrees

FIG. 59

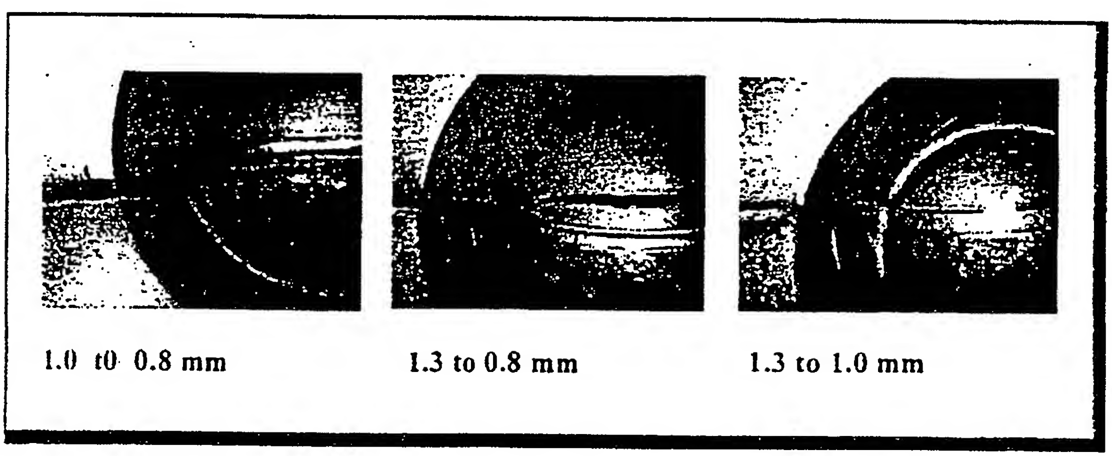
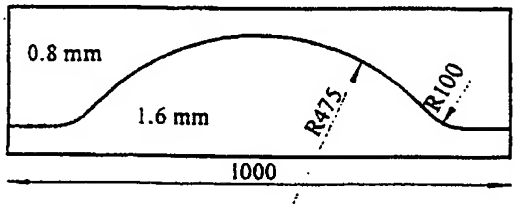
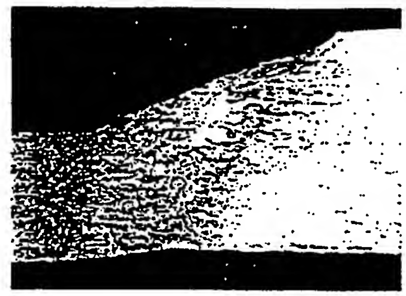

1.0 t0 0.8 mm
1.3 to 0.8 mm
1.3 to 1.0 mm

FIG. 60

Part I

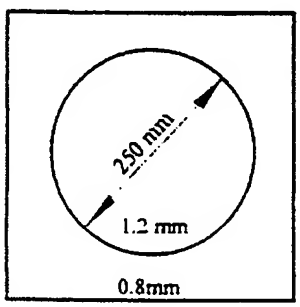


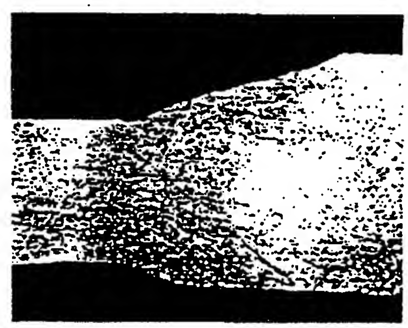


Cross section of welds

Welding Parameters:
Laser power: 1750+1900 W
Beam rotation: 30 degrees
Weld speed: 5 m/min

Part II





Cross section of welds

Weld Parameters:
Laser power: 1500+1700 W
Beam rotation: 30 degrees
Weld speed: 5 m/min

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 99/00547

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B23K26/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 96 32219 A (TWENTYFIRST CENTURY CORP) 17 October 1996 (1996-10-17) the whole document ---	1,2,4-9, 11-14, 16-18,20
P,X	WO 98 51442 A (FRAUNHOFER USA RESOURCE CENTER) 19 November 1998 (1998-11-19)	13,16
A	the whole document ---	1,3,5,9, 20
A	PATENT ABSTRACTS OF JAPAN vol. 010, no. 047 (M-456), 25 February 1986 (1986-02-25) & JP 60 199585 A (TOSHIBA KK), 9 October 1985 (1985-10-09) abstract --- -/--	1,4,9,13

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 October 1999	14/10/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Aran, D

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 99/00547

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
P,A	WO 98 39136 A (AUTOMATED WELDING SYSTEMS INC.) 6 September 1998 (1998-09-06) page 3, last paragraph -page 9, paragraph 1 page 11, last paragraph -page 12, paragraph 1 page 16, paragraph 2 -page 17, paragraph 1 page 18, paragraph 2 - paragraph 3 page 20, paragraph 2; figures 2,4-7 ---	1
A	PATENT ABSTRACTS OF JAPAN vol. 1995, no. 06, 31 July 1995 (1995-07-31) & JP 07 060470 A (SUMITOMO HEAVY IND LTD), 7 March 1995 (1995-03-07) abstract -----	1,9,13

1

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Int· ·tional Application No
PCT/CA 99/00547

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9632219 A	17-10-1996	US 5591360 A	07-01-1997
WO 9851442 A	19-11-1998	NONE	
JP 60199585 A	09-10-1985	NONE	
WO 9839136 A	11-09-1998	CA 2199355 A	06-09-1998
		AU 6203198 A	22-09-1998
JP 07060470 A	07-03-1995	JP 2828879 B	25-11-1998

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